THE EARLY DEVELOPMENT
OF THE
REFLECTING TELESCOPE
IN BRITAIN

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ABSTRACT

The first effective demonstration of a telescope using reflecting optics was made by Isaac Newton, and his invention was given widespread publicity by the Royal Society of London in 1672. Newton's instrument was closely associated with the introduction of his new theory of the nature of white light and colour, and for Newton his telescope's practicability remained important to the acceptance of his optical theory. Newton's telescope, influenced to some extent by the earlier work of James Gregory, encouraged the Royal Society to promote more ambitious trials, but instruments by Robert Hooke and Christopher Cock, and by Newton himself, achieved only limited success.

Renewed interest in the reflector followed its re-emergence in Newton's <u>Opticks</u> of 1704. John Hadley's successful revival of Newton's instrument led in turn to the establishment in London of competitive commercial manufacture of reflectors in the early 18th century, and by 1740 the market was dominated by the instruments of James Short.

Contemporary references to the reflecting telescopes of Newton and others have been analysed to allow the historical development of this work to be established more reliably, and to propose a relationship between the various instruments that may be ascribed to Newton. The emphasis has therefore been placed on the instrumentation itself, on practical detail, and on questions of provenance.

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CHAPTER 1 INTRODUCTION

From its earliest days the telescope proved one of the most potent instruments of science, and one which allowed the visual sense to be extended in a dramatic and previously unexpected way. Its value in innumerable undertakings was rapidly appreciated, but it was in two fields that it became the central and indispensable tool. In observational astronomy it was the means for revealing an apparently infinite extension of celestial phenomena. With its application to graduated instruments, the telescope revolutionised cosmography and positional astronomy, and the precision that could increasingly be achieved was an essential element in the development and verification of physical and dynamical models.

Encouraged by the potential of the instrument, but frustrated by technical limitations, astronomers and patrons of science pressed for ever greater improvement in the power of their telescopes; and the skills demanded placed the optics and fabric of the telescope at the forefront of practical expertise. Although the advances made in the effectiveness of the telescope therefore reveal to some extent the creative inter-relation of the scientist as practitioner and the artisan, they rely also on economic factors which have constrained development. Thus, during the 17th century, the availability of optical glass of even moderate quality followed only from commercial pressure for superior domestic glass. Similarly, it was the growing popular demand for optical devices that led to improvements in optical lapidary techniques and enabled a number of more specialised craftsmen to rise above mere spectacle-making, and to place themselves in a position where they could respond to more demanding commissions.

Thus, apart from the obvious importance of the development of the telescope to the history of astronomy itself, it provides an index of the growing competence and capability of the professional support available to the scientific community.

In view of the alacrity with which the first telescopes were greeted it is perhaps not surprising that the history of this 'miraculous' invention proved to be of early and enduring interest. The first historical account appeared within a generation of the supposed date of invention(1), but it is only very recently that the detailed evidence for an assessment of the circumstances surrounding the invention has become widely appreciated.(2) Such historical studies as have been made, however, have concentrated on the early development of the refracting telescope, that is one employing glass lenses to project an image into the eye, which was the first form of telescope to emerge. The imaging properties of curved mirrors had long been considered as analogous or complementary to those of lenses, and the geometrical optics of reflecting and refracting surfaces had been developed in the closest association. Inevitably, therefore, attention would be given to producing telescopes in which the images were formed by reflecting elements. Yet early reflecting telescopes, probably from the historical accident of their not having been the 'first' telescopes, have received scant critical attention in the literature.

P.E. Ariotti has recently examined the claim for the effective genesis of the reflecting telescope in Italy very shortly after the emergence of the refractor, and has pointed to the simplistic accounts normally given for the invention of the reflecting telescope.(3) It is generally claimed that Isaac Newton, having discovered the composite nature of white light and having deduced that this denied the possibility of improving the refracting telescope, constructed the first reflecting telescope in 1668, drawing perhaps on an earlier suggestion by James Gregory. While some authors have discussed the possible constributions of earlier workers, such as Marin Mersenne, Ariotti has given the first critical assessment of Continental achievement.

The reflecting telescope has a separate history to that of the refractor, and its development has been subject to different constraints. It achieved very considerable practical success in the 18th century in the hands of the maker James Short, and after his death the instruments of William Herschel continued the dominance of reflectors over refractors in observational stronomy. This very success, and the continued use of reflecting optics in the majority of large instruments, makes it surprising that the early development of reflecting telescopes has not been more closely examined. This is perhaps all the more surprising since this work is so closely identified with the early genius of Newton and the evolution of his historically important optical theory.

The aim of the present study is to help redress this imbalance by examining the period of early development of the reflector in Britain up to the time in the 18th century when commercial manufacture of such instruments was firmly and successfully established. It has not been my intention to delve into the pre-history of such work in the developing tradition of geometric optics, since this has little relevance beyond the appreciation of the complementary nature of dioptrics and catoptrics. The role of instrumentation in the experimental philosophy of 17th-century England has been assessed by others, notably J.A. Bennett, and so this theme has been developed only where it is of direct relevance to the reflector.[4] Rather, this study is intended as a gathering of the principal sources relating to late 17th- and early 18th-century reflecting instruments in the hope that this will allow the historical development of the telescope, and particularly of Newton's role in its realisation, to be more clearly established. The emphasis therefore has been placed on the instrumentation itself, on practical detail, and on questions of provenance.

Although reflecting telescopes were discussed in theoretical terms in Italy and France in the first half of the 17th century, the considerable technical challenge their execution posed meant that they appeared neither a practical nor an attractive alternative to the early refractors, for all the faults of the latter.

In the early 1660s James Gregory attempted to demonstrate that such a telescope was realisable. With access now to specialised commercial expertise and to the improved optical techniques that were transforming the astronomical refractor, the attempt met with some success. His instrument was little known but it interested Robert Hooke, then the most original optical experimentalist of his day and a pivotal figure in the recently established Royal Society of London. The telescope undoubtedly influenced Hooke's own work and conditioned his later response to the challenge of Isaac Newton's instrument. The practical development of telescope optics had been a concern in the 1640s and 1650s of a group of mathematicians and astronomers, including Christopher Wren, closely identified with Gresham College and the origins of the Royal Society, and it continued to form an important part of the Society's programme in the 1660s. Newton's reflecting telescope, the first demonstrably successful instrument, was seized upon by the Society and proclaimed as an invention of significance in 1672. After the initial excitement and flurry of activity, technical problems were still seen to stand in the way of progress, and the instrument was soon all but forgotten. Conceived in isolation from the practical optics of London, but nonetheless owing something to Gregory, his telescope was the means of introducing Newton to the Royal Society, and was used by him as a vehicle to gain acceptance for his theory of the nature of white light and colour.

With the death of Newton's principal optical critic Robert Hooke Newton at last agreed to publish his Opticks in 1704. In this the reflecting telescope re-emerged to provide support for Newton's contention that the images formed by lenses were inescapably coloured by dispersion. Newton's description of the telescope however was the inspiration of other workers, notably John Hadley, and Newton lived to see sizeable reflecting instruments being compared favourably with some of the largest refracting telescopes. Hadley's successful revival of Newton's instrument led in turn to the establishment in London of competitive commercial manufacture of reflectors in the early 18th century. These instruments were overtaken in quality by about 1740 by the reflectors of James Short, in whose hands they reached a perfection not surpassed in Short's lifetime. At a period when the reputation of the principal London mechanicians was such that they were equipping observatories and expeditions across the globe, Short's position as the leading telescope maker was undisputed.

Reasons for the rapid development of the London instrument-making trade in the early 18th century have been advanced elsewhere, and will not be repeated here. Studies of the structure of sections of the trade have demonstrated the growing stability and reputation of the London market at the close of the 17th century and an increasingly complex relationship of specialist makers and retailers.(5) The expansion of the London market in the early 18th century has been explored by G.L'E. Turner and others in terms initially of a response to the rise of the new experimental natural philosophy of the Newtonians and a consequent explosive interest in scientific enquiry and instrumentation.(6) Economic, social and technical factors which favoured expansion of the London market, but not that for example of Paris, have been discussed by M. Daumas.(7)

The period of this survey has been chosen to lead up to published work on mid 18th-century London commercial manufacturers by D.J. Bryden and Turner.(8) French activity, beginning only in the 1720s, has been described by Daumas and S.L. Chapin.(9) British amateur experimentalists of the second half of the century have most appropriately been discussed in terms of the association of their work with that of William Herschel.(10)

The evolving mechanistic optics of the Newtonians, central to optical discussion of the period, and the implications for the introduction of achromatic dioptrics, have been assessed in a European context by P.A. Pav and H.J. Steffens.(11) Discussion of physical optics has therefore been restricted to aspects of specific relevance.

I have used the standard terminology to describe instruments and components. Thus if the image of a distant object is formed by a convex lens the instrument is a refracting telescope or refractor; and if by a concave mirror it is a reflecting telescope or reflector. In both cases the imaging element is referred to as the objective. In the 17th century and before the term 'glass' for an objective was often applied both to mirrors and lenses. The use of a concave eyelens denotes a Dutch or Galilean refractor, often referred to as an 'ordinary tube' to distinguish it from the refractor with a convex or compound eyelens. The latter is either an 'astronomical' telescope, or a 'terrestrial' telescope if there is an erector lens. Reflectors are classified by the name popularly associated with their introduction, and the optical systems are explained in the text. In the Newtonian, Gregorian and Cassegrain forms two mirrors are employed to form the image, which is then examined by the eyepiece. The principal mirror is often referred to as the 'primary', and the smaller subsidiary mirror as the 'secondary'. In the Herschel or 'front-view' form, only the principal mirror is used, but it is inclined slightly to the line of view. The mirrors discussed here are usually of metal, but occasionally of glass with a reflecting rear surface. The terms 'mirror' and 'speculum' are used interchangeably and are not intended to imply construction in a particular material; similarly, use of the 18th-century alloy normally known as Speculum Metal should not be inferred for specula. The shapes of non-spherical optical surfaces are normally given by the conic described by the section of the mirror through its axis. Physical sizes are given where appropriate in feet and inches, and usually in abbreviated form, e.g. 2'6": this form of abbreviation is not used for angular sizes.

The only other convention which should be noted is that, unless otherwise stated the dating is always given according to the Julian 'old style' calendar, which remained in use in Britain up to the introduction of the Gregorian calendar in 1752. After this dates are given in 'new style', which is advanced by 10 days. The dates of material of Continental origin are normally converted to 'old style'. For simplicity the modern convention for year numbers has been used in the main text, but double denominations for the first quarter of the year are used in the references. The occasional unascribed translations are by the author.

Notes and References

1. Borel (1655-6): see van Helden (1977), 58-64.
2. Van Helden (1975), van Helden (1977).
3. Ariotti (1975). He was apparently unaware (note 4) of the early account by H.C. King in which Cavalieri's work is mentioned but not discussed: King (1939).
4. Bennett (1975), Bennett (1980).
5. For example Brown (1979), Court & von Rohr (1929-30).
6. Turner (1973).
7. Daumas (1953).
8. Bryden (1968), Bryden (1970), Turner (1969), Turner G.L'E. 'The Number Code on Reflecting Telescopes by Nairne and Blunt' J. Hist. Astron. 10 (1979) 177-184.
9. Daumas (1953), Chapin S.L. '"In a Mirror brightly": French Attempts to build Reflecting Telescopes using Platinum' J. Hist. Astron. 3 (1972) 87-104.
10. Turner (1977).
11. Pav P.A. 'Eighteenth-Century Optics: The Age of Unenlightenment' thesis, Indiana University, 1964; Steffens (1977).

CHAPTER 2 A BACKGROUND PROVIDED BY THE REFRACTING TELESCOPE

The importance of the telescope for science, and particularly in the establishment of a modern cosmological philosophy, is widely appreciated. The influence of science on the development of the telescope, however, is less well understood. In a recent analysis A. van Helden has reassessed the instrument's 17th-century role and has demonstrated that influence from theoretical studies was minimal, a conclusion previously suggested by M. Daumas.(1) Instead, van Helden sees the telescope's evolution as depending on specialist skills emerging from manual traditions and constrained by practical and economic factors. Although limited by technical problems, the instrument's potential for improvement was always possible to comprehend hopefully, if not to realise in practice.

It was against the background of the refracting telescope's increasing contribution, and enduring problems, that the reflecting telescope was introduced in Britain in the second half of the 17th century. Since contemporary attitudes to the refractor necessarily conditioned reactions to the reflector, it has been thought desirable to provide a brief sketch of the history of the refractor in the period being considered.

In recent years the refractor has undergone a renaissance through the work of Professor van Helden, whose painstaking work has for example allowed the invention of the telescope to be set convincingly in the closing years of the 16th century.(2) Its significance and potential was first appreciated in 1608: the attempts of the Dutch authorities to keep the discovery secret were unsuccessful, and news of the invention spread rapidly.(3) Optical components readily available from spectacle makers permitted only small magnifications, and so a number of optical workers set about the difficult task of grinding the shallower curves required for longer focal length lenses. The quality of such work was low and although it satisfied the principal demand for perspectives for land and naval use it was not sufficient for astronomical work. Unable to obtain suitable lenses, Galileo was forced to learn to grind his own, and to seek skilled workers whom he could commission. He was successful enough to produce an instrument in 1610 with which he could detect the satellites of Jupiter and, in the following year, spots on the Sun. The publication of his results produced a sensation and was a principal factor in bringing the novelty of the telescope to a wide audience. In particular, Galileo's work stimulated Johannes Kepler to undertake in 1610 the first theoretical study of image formation by lenses, published in his Dioptrice, considered as the starting point of modern optics.(4) In this Kepler first proposed the use of a convex lens as the eye-lens in place of the concave lens that had been used exclusively up until then in the 'Dutch' or 'Galilean' form of the instrument: although this produced an inverted image, it could, he said, be erected by using a third convex lens. These ideas were not put into practice by Kepler, and van Helden allows that this is the only clear instance in which practice did not preceed theory.(5)

Galileo provides an early but prominent example of the gifted amateur practitioners who were peculiarly attracted by the unexplored possibilities of optical instruments. Principally academics, teachers and clerics, they became involved in the practicalities of designing and grinding lenses, often stimulating discussion and encouraging praise of their work. The successful construction of microscopes and telescopes which were intended to excel bestowed prestige and proved remunerative. Thus in Italy Galileo and Torricelli produced instruments for their own use but also to satisfy purchasers, as did other notable natural philosophers such as Pierre Borel, Adrien Auzout, Chérubin d'Orléans, Christiaan Huygens and Robert Hooke.(6) Often such amateurs were assisted by artisans, who through the association developed particular skills which were then turned to commercial advantage.

Galileo's early lenses came from renowned glass making centres such as Venice, where workers were already specialising in telescope lenses.(7) When a glassworks for fine glass was established in Florence Galileo sponsored a skilled lapidary named Ippolito Francini (fl. 1619 - d. 1653) who produced his later lenses, no doubt under Galileo's personal supervision.(8) These lenses however were particularly fine for their period: indifferent glass and comparatively poor techniques elsewhere meant that astronomers were often unable to confirm Galileo's discoveries.(9) Good telescopes were very hard to obtain and consequently expensive, and few astronomers had access to them; the instrument-makers' patrons were in any case principally concerned with the telescope's terrestrial use. Only a very few longer telescopes, with therefore higher magnification, were in use at this early period, notably those of Galileo, and Thomas Harriot in England.(10) An inescapable drawback of 'Dutch' telescopes was that they had a very small field of view, which restricted their usefulness even at the low magnifications required to view the very limited range of celestial objects that could be examined. At higher magnifications of 20 to 30 times this became an increasing disadvantage, allowing for example only a small portion of the Moon or just a part of Jupiter's satellite system to be seen at one time.(11) A consequence of this was to impose a practical ceiling on the useful size of instruments, so that for example naval telescopes, designed for use on a moving vessel where the narrow field of view would prove particularly troublesome, remained small.

This problem was not encountered in the double convex lens telescope proposed by Kepler, and later to be known as the 'astronomical' telescope. Its merits however took a considerable time to be appreciated, and it did not pass into widespread use until the 1640s. In seeking reasons for this delay van Helden has proposed that it was due to the conservatism of the market.(12) The basic Kepler form producing an inverted image would seem to offer no advantage over the familiar 'Dutch' form: indeed it would seem likely to be even more difficult to use. Rather, there would be a strong instinctive preference for the 'Dutch' form's erect image, particularly in view of the telescope's principal use (even by patrons of professional astronomers) as a terrestrial instrument where only an erect image would be acceptable. The addition of an erecting lens in Kepler's scheme would be seen as an unnecessary and expensive complication to produce what was merely a substitute for the existing 'Dutch' telescope. Moreover, the much wider field of view of the 'Kepler' form, which was its main advantage, could not be appreciated unless the instrument was actually constructed and tried. Certainly, once the instrument became commercially available its merits were quickly recognised and it soon became popular.

The strongest claim for priority in introducing the 'Kepler' form of telescope is that of Francesco Fontana (1580-1656), an optical worker of Naples. Fontana was one of a handful of lens grinders who were making slow but perceptible progress in the area of principal difficulty with telescopes - the accurate shaping of the spherical surfaces of objective lenses - and in the process were gaining respect as skilled specialists in a new art. In his day Fontana was perhaps the most successful at fashioning higher quality lenses. In the late 1630s his fame was spreading beyond Naples, and Galileo grudgingly admitted that his instruments were superior to those of Francini.(13) Fontana appears to have made Kepler's form of refractor from the early 1620s, and to have seen it adopted for most serious astronomical work in Italy by 1640.(14) An important early application of the Kepler instrument was in the exhaustive work on sunspots conducted by the Jesuit Christoph Scheiner in Italy and published in 1630: towards the end of his research Scheiner, who viewed the Sun by projection, used the 'Kepler' form, and van Helden has suggested that he was influenced to do so by contact with Fontana.(15)

The Kepler form of refractor was largely unknown outside Italy until the late 1640s. An important exception however must be made for the astronomical work of William Gascoigne, one of an enthusiastic group of talented amateur astronomers in the Midlands of England. Gascoigne had by 1639 demonstrated the other principal advantage of the Kepler instrument(16): because the objective brings the light to a positive focus, where the image is examined by the eyepiece, a movable micrometer can be introduced at the focus, enabling the angular size of the object viewed to be measured. Gascoigne was killed in the Civil War, but his surviving papers were an important influence on John Flamsteed and Robert Hooke, both of whom were actively concerned with the introduction of telescopic sights on astronomical instruments. It is clear from Gascoigne's correspondence that he was familiar with the published work of Kepler and Scheiner and was presumably influenced by them in constructing this form of telescope.(17)

In 1645 the Bavarian Capuchin friar Antonius Maria Schyraeus de Rheita published an astronomical work which included a discussion of telescope optics and described the 3-lens erecting terrestrial telescope first proposed by Kepler, and also gave a veiled account of the latest invention of a 4-lens instrument, the first to include a field lens.(18) Schyrle was at pains to stress not only the very wide field of view of these instruments, representing a dramatic advance over the 'Dutch' form for terrestrial observations, but also that those unable to construct their own telescopes of this type according to Schyrle's instructions could obtain them from Johannes Wiesel of Augsburg. Wiesel (c1583 - post 1660), already a celebrated optician, had apparently been taught by Schyrle, and again van Helden has been able to suggest the possibility of a personal association with Scheiner.(19)

Although the advantages of the terrestrial telescope were now increasingly recognised, and it began replacing the 'Dutch' or Galilean form, it was not suitable for astronomical work. The cumulative effect of the aberrations of the four lenses was too great, and so for astronomical purposes it was used in Kepler's 'astronomical' form with merely an objective and an eye-lens, although compound eyepieces were used later. Astronomers came to accept the inverted image, and to all intents and purposes the astronomical telescope was now separated from the terrestrial. Free of the limiting restrictions of the Galilean telescope, there was now distinct advantage to be gained from increasing the focal length of objectives to obtain higher magnifications.

A basic problem for the optical worker was the difficulty of obtaining glass of a suitable quality for telescope lenses. The best glass was initially made in Italy, and the success of early Italian instruments depended to a large extent on the comparative excellence of

Venetian table glass and mirror glass. In the course of the 17th century the local production of quality glass was established in Holland, England (in the 1660s) and finally France.[20] However, glass production was often uncertain, the composition of the glass was variable, and the mix contained bubbles, striations and inclusions. The method of removing glass from the pot and rolling it in layers gave rise to structural properties which adversely affected its optical characteristics. It was only by the most careful preparation and inspection of his glass that the optical lapidary could find pieces of acceptable quality. The successful worker established a special relationship with his glass founder that enabled him to select from the best spectacle and mirror glass. Even so the most discriminating makers found that they ultimately had to reject the majority of pieces that they had culled.[21]

Probably of greater importance however was the general improvement in optical lapidary technique, and the establishment of a number of specialist and respected craftsmen whose skills were increasingly able to realise the wishes of astronomers. A contributory factor was the changing pattern of patronage found with the creation of experimentally orientated academies such as the Royal Society of London and the Parisian Académie Royale des Sciences. These not only sponsored, encouraged and published optical and astronomical research, they also provided convenient forums for priority disputes and polemics which tended to heighten awareness of apparatus and of the role of skilled artisans in the solution of contemporary problems in science. The improved status of the principal instrument makers is seen to some extent in the 17th century, but markedly in the 18th, in their contribution of scientific papers and membership of academic bodies.

Van Helden has demonstrated the improved quality of lenses most clearly by noting a comparison of the resolving power of similarly sized lenses of Venetian glass by Galileo and by Giuseppe Campani, the principal commercial objective maker of the second half of the century. The resolution of a Campani lens of about 1660 was found to be around three times better than that of Galileo's lens of 1610, and would have been hard to improve upon.(22)

The important consequence of this developing expertise was that optical workers were able to achieve higher magnifications using longer focal length lenses with larger apertures. Van Helden has shown that the average size of good telescopes rose from 6-8 ft in 1645, to 10-15 ft in 1650, 25 ft in 1660, and 40-50 ft in 1670.(23) Although objectives were subsequently produced with extreme focal lengths, virtually no work of importance was done with them, and the maximum useful size for telescopes in the second half of the century can be set at about 35 feet.(24) The only exception to this being that some planetary discoveries were made at the Paris Observatory by J.D. Cassini using longer instruments, but this may largely be attributed to Cassini's great skill as an observer.(25)

The most significant makers at this period were the Italians Eustachio Divini (1620-1695) and Giuseppe Campani (1635-1715).(26) Divini established a shop in Rome about 1646, and by 1650 he had a considerable reputation and his telescopes were being imported into France.(27) Campani came to Rome about 1650 and may have been apprenticed to Divini, starting production on his own about 1660. The joint astronomical work he undertook with Cassini before the latter's appointment at Paris stood him in good stead, and led to many lucrative commissions for the Paris Observatory, a number also being placed with Divini. The success and publicity achieved by Cassini helped establish Campani and Divini firmly as the principal makers of the day, but tended to eclipse contemporary work by French opticians. They became great rivals and there was considerable interest in comparisons between their work, but Campani's objectives were generally reckoned to be better.(28) Campani's secret apparently lay in the most careful selection of glass, and in the use of exacting procedures to prepare the lens surfaces using a wide range of patterns for each lens: in particular Campani invented and used a comparatively sophisticated form of lathe. His techniques and apparatus were jealously guarded in his lifetime, as were those of most other makers, but were described some time after his death.(29) He was the first to use a specially printed sheet to test the resolution of telescopes.(30)

In Britain, also, the skills of producing large telescopes were found only in a few specialist practitioners. Richard Reeves, roughly contemporary with Divini, benefited from the tutelage of the astronomers that came to be associated with the Royal Society, and he enjoyed the Society's patronage in its early years, producing a number of sizeable instruments.(31) Christopher Cock (fl. 1660-96) may originally have been his pupil, but was soon a rival. He succeeded Reeves in the Society's favour, and like Reeves gained prestige as well as orders from the association. A 50 foot lens supplied by him to the Danzig astronomer Johann Hevelius in 1670 was said by Hevelius to have been the best he had yet used.(32)

An important influence in this most active period was the Dutch mathematician and astronomer Christiaan Huygens (1629-95). Huygens and his brother Constantine constructed a number of telescopes of high quality from the mid 1650s, and in 1661 during a visit to London he discussed his techniques at the Royal Society. He was familiar with Reeves and his work, and from 1666 he was based in Paris where he took a close interest in the acquisition and merits of the instruments of Campani and Divini at the Observatory. His wide correspondence and his reputation as the leading optical authority helped ensure that news about telescopes was soberly assessed and circulated.

Although the focal lengths of objectives became longer, for practical reasons their diameters remained relatively small, and their apertures were normally further restricted by objective stops. Campani was able to make his objectives rather broader than other makers, and yet the diameter of the 34 foot objective he supplied to Cassini in 1672 was only 5½", which would be reduced to about 4" or less in use.(33) By contrast, Reeves' 60 foot objective of 1664 was also 5½" across.(34) Thus the majority of good astronomical objectives in the third quarter of the century will have been only a few inches across. In general they were produced by techniques which were merely an extension of the manual tradition of spectacle lens making.(35) Lenses were ground against metal tools or patterns, which were concave shapes in metal, perhaps twice the diameter of the lenses they were intended to fashion. These might be forged in iron, or more likely cast in brass or another alloy, a wooden or metal model having been used to form the mould. The tools then required to be ground and polished to the correct concave spherical shape, by hand or on a lathe, to match profile gauges filed from sheet brass to an accuracy that ultimately determined the quality of the lens figure. The glass blank, having been polished plane to check its quality and reduce it to a single gathering layer, was first shaped roughly in an oversize tool with coarse abrasive. Then the glass was held by a handle adhered to one face, and the other was ground in the tool using progressively finer abrasives. Each maker had preferred abrasives, whose properties of course affected the choice of alloy used for the tools. Campani and Huygens used emery powder, successively removing excess and achieving a finer and finer abrasive. Cock used a fine white sand in the same way. Final grinding was done with a material such as tripoli powder or tin-putty. Polishing was done with paper or fabric attached to the tool and using a very soft paste abrasive or pitch or no abrasive at all. There was considerable variation in the use of tools. Cock and Chérubin used a single tool through the whole grinding and polishing process, a technique that soon fell from use. Campani seems to have interchanged tools frequently, finishing the grinding and polishing on those of greatest accuracy. Huygens produced matched concave and convex tools to allow the concave tool to be pitch-polished on the convex, and amongst other methods used a separate concave stone tool for cloth polishing of the lens. Clearly a great deal depended on the manual dexterity and skill of the optician and on individualised procedures in what was largely a trial-and-error process. Towards the end of the century the extremely long focal length objectives produced by workers such as Niklaas Hartsoeker in France led to the development of special procedures designed to generate the very shallow curvatures required.

During the second half of the 17th century there was continued interest in the use of lathes as lens-grinding machines. Lathes were certainly used increasingly for the generation of accurate concave grinding tools. These were produced by rotating the unfinished tool against the cutting surface of a lathe tool fixed at the end of a long rod pivoting in a horizontal plane (or, in some versions, a vertical plane) about a point at the far end of the lathe bed. The length of the rod defined the radius of curvature of the tool and therefore of the glass surface, but the lathe of this type invented and used by Campani was of a considerable size.(36) By attaching the lens blank to the end of the rod of such a lathe the lens could be machine ground. Although there was considerable experimentation with lens-grinding machines of this and other types from about 1650 it seems clear that such devices could only be used satisfactorily for preliminary grinding of objectives, and that finishing and polishing were done by hand. It was widely believed that Campani used a lathe to make his lenses, but although he may have been assisted by one in making some lenses it is certain that his finest lenses were made manually with a tool and without the aid of a machine.(37) Lens-grinding and polishing engines were designed by Hooke, Chérubin, Huygens, Marshall and others; and towards the end of the century mechanical devices were achieving a fair degree of success, but it was not until the 1730s that an automatic machine was constructed.(38) The main changes in the late 17th and early 18th centuries were in detailed manual technique, particularly in the use of more specialised tools for particular phases of the work, and were influenced by a better understanding of thermal and mechanical factors.

Although the improvement in the quality of objectives resulted largely from an increased ability to grind truly spherical surfaces, from an early period it had been appreciated that spherical surfaces were not adequate. Kepler had pointed out that a spherical lens does not bring light to a focus at a point, but that the outer zones of the lens have slightly shorter focal lengths: the effect was later distinguished as spherical aberration. Kepler went on to propose that the correct form for a lens would be one with hyperboloid faces.[39] The desirability of hyperbolic surfaces became more generally known after the detailed geometric treatment given to lens systems by René Descartes in his Dioptrique of 1637.[40] Although, as van Helden has explained, it is usually postulated that Descartes' analysis of the defects of spherical lenses led to minimising the curvature of lens surfaces and seeking high magnification through increased focal length of the objective, it is difficult to credit Descartes as the impetus behind this effort.[41] In practice, the realisation that increased curvature of the objective led to less well defined images came at an early stage through practical experience. Galileo for example had been obliged to stop down the objectives of his first telescopes to mask off the areas of greatest curvature before they could be used astronomically.[42] The fact that the problem lay with the quality of the objective would have been readily apparent when it was seen that using a higher power eye-piece theoretically increased magnification but in fact did not improve definition. The aperture of the lens was closely related to the focal length, and so to obtain a brighter image the two had to increase together if chromatic effects were to be minimised. The move to adopt progressively longer focal lengths was then a natural one, and it was one which had certainly begun in the 1630s before Descartes' work was published.[43] The conclusions of Descartes, and later of Isaac Newton with his analysis of the hitherto unexpected cause of colouration effects in images, did however reassure astronomers that the trend to longer telescopes was justified.

By the time that Newton's reflecting telescope was made public in 1672, Hevelius was preparing a telescope of immense and almost unmanageable proportions, with a 140 foot lens by Tito Burattini. S.A. Bedini has discussed some of the prominent long telescopes of the latter part of the century and has described their eventual use without solid tubes as 'aerial telescopes'.(44) The impact of these instruments seems to have been purely as technical <u>tours de force</u>, although some (notably Constantine Huygens' lenses belonging to the Royal Society) remained in occasional use into the 18th century.(45) However by that time they were considered largely irrelevant, and astronomers were increasingly concerned with the problems of positional astronomy and geodetics, and with the development of graduated rather than purely observational instruments.

Descartes' advice did however have the effect of encouraging a number of experiments in time-consuming but ultimately fruitless attempts to obtain hyperbolic surfaces. Descartes himself commissioned Guillaume Ferrier, a skilled mechanic and professor at the Parisian Collège Royal, to grind hyperbolic lenses using specially cut templates produced by the geometrician Claude Mydorge, but the attempt failed.(46)

Amongst those stimulated by Descartes' suggestions was Isaac Newton, who in the course of his earliest optical researches at Cambridge "applyed my self to the grinding of Optick glasses of other figures than <u>Spherical</u>".(47) Apart from this reference his interests are known only from early optical manuscripts, published in recent times by A.R. Hall but which remained unknown to Newton's mathematical contemporaries.(48) Hall has concluded that Newton's work was undertaken briefly in mid 1665 and was almost certainly speculative -

the 'application' being mental rather than practical. The grinding engines sketched by him anticipated Christopher Wren's demonstration that single and double-sheet hyperboloids of revolution could be generated by lines skew to the solid's axis.

Of the London scientists concerned with practical optics, both Sir Paul Neile and Wren took an early interest in non-spherical lenses.(49) Wren's method was made public at the Royal Society in mid 1669, some years after its development, and a model of a grinding engine for hyperbolic lenses was produced. Robert Hooke announced at the same time an engine of his own for hyperbolic or elliptic lenses, and in his capacity as Curator of Experiments he was asked to put both Wren's machine and his own into practice. After considerable delay and several reminders Hooke eventually decided in early 1671 that his own method was better. Whatever their theoretical operation, there were doubts about whether either device was practical, and there is no subsequent record of lenses having been successfully ground.

It is possible that the attempts of Neile and Wren may have been provoked by the futile efforts of the French inventor de Son to grind parabolic lenses while in London in late 1665. De Son had proved a success at Court and was promoted by Sir Robert Moray, the Society's influential Vice-President, although his mathematical abilities were privately disparaged: accounts of his lenses appeared in the Society's <u>Philosophical Transactions</u>.(50) Apparently more successful was Francis Smethwick, who was elected a Fellow of the Royal Society in 1667, and had been a pupil of the mathematician William Oughtred: Smethwick was the inventor of a method of grinding non-spherical lenses, for which he held a patent, and was encouraged by Sir Paul Neile.(51) A $6\frac{1}{2}$ inch telescope exhibited at the Royal Society in June 1671 was well received, and his progress was followed with interest by Huygens: however, he was a perfectionist who worked slowly "because he makes use of no help except from a servant working in his room", and the success of Newton's reflecting telescope made him throw up his telescope work immediately.[52] About two years later he produced a microscope with supposedly conic section lenses which was politely received, and in 1685 the design of his grinding engine was shown to the Society.[53]

On the Continent Christiaan Huygens was amongst those who had unsuccessfully experimented with conic section lenses, from which he believed "nothing can be hoped".[54] Johann Hevelius had made expansive but unfounded claims in 1665 to have mastered this art ten years beforehand[55], but in 1671-2 there was considerable interest in whether Johann Ott of Zurich had achieved success with lenses that he had published in 1670.[56]

Conic section surfaces were in fact to remain beyond the reach of 17th-century optical workers: the first to be successfully produced were the parabolic mirrors of John Hadley, and later James Short, in the early 18th century. The issue was however very much alive in the late 1660s, and the recognition that the technical problems of refractors of extreme length limited astronomical advance and that a new departure was required was an essential element in determining the reaction to Newton's reflecting telescope.

In announcing his theory of the nature of colour in 1672, Newton showed how chromatic effects in telescope images should be interpreted, and demonstrated that such effects were vastly greater than the small effects of spherical aberration which the grinders of non-spherical lenses aimed to eliminate. An unfortunate consequence however of Newton's vigorous defence of his theory in the face of criticism from Robert Hooke was his suppression of discussion of the effect of combining materials of different refractive properties. In the course of his pioneering work on microscopy in the early to mid 1660s Hooke had performed a number of experiments on compound fluid and glass lenses, and such work might well have borne fruit had Newton's response been different.(57) As it was, the achromatic lens, in which different types of glass were combined in such a way as to eliminate chromatic effects, only made its public appearance in 1758, by which time the reflecting telescope had become firmly established as the most effective instrument in observational astronomy.

Notes and References

1. Van Helden (1974), 49; Daumas (1953), 31.
2. Van Helden (1975), 259.
3. Van Helden (1977), 25-6.
4. Kepler (1611), see Van Helden (1976), 15.
5. Van Helden (1974), 49.
6. Daumas (1953), 28.
7. Bedini (1966), 689.
8. Ibid, 690.
9. Van Helden (1974), 52.
10. See North (1974).
11. Van Helden (1976), 26.
12. Van Helden (1974), 41-2.
13. Van Helden (1976), 28. Kircher however still preferred the instruments of Torricelli: Clay & Court (1932), 257.
14. Van Helden (1976), 28.
15. Scheiner (1630), see Van Helden (1976), 25.
16. King (1955), 96, citing Sherburne's Sphere of Marcus Manilius (London 1675).
17. Rigaud (1841) I, 39.
18. Schyrle (1645), see van Helden (1976), 30.
19. Van Helden (1976), 32. A price list indicating the range of telescopes available from Weisel in 1647 is reproduced in Court & von Rohr (1930-31).
20. Daumas (1953), 32. On English glass production see e.g. Powell (1923).
21. Daumas (1953), 33. The earlier practice of casting convex glass blanks is discussed briefly by Bedini (1966), 688-9.

22. Van Helden (1974), 45-6.
23. *Ibid*, 46-7.
24. *Ibid*, 47.
25. Daumas (1953), 65; Bedini (1967), 401.
26. The dating is that of Bedini (1966) rather than Hall & Hall (1966), 228.
27. Daumas (1953), 65.
28. Thus, for example, Henry Oldenburg, Secretary of the Royal Society of London, relayed to Robert Boyle the news from Rome that "*Campani* hath had ye advantage over Eustachio de Divini. ye Great Duke of Tuscany and Prince Leopold, after they had tryed both, found those of Campani better ...": Hall & Hall (1966), 629: letter of 5 December 1665. It has been suggested that Campani was the son-in-law of Johannes Wiesel of Augsburg, based on a reference to him by Balthazar de Monconys in the 1640s (Court & von Rohr (1929), 213), but this is likely to have been Daniel de Pierre (Hall & Hall (1971), 598).
29. Bedini (1966), 691-2; Bedini (1961).
30. See Hall & Hall (1966), 554 n2 for the publication of this.
31. Reeves will be discussed in the section devoted to the reflecting telescope of James Gregory.
32. Hall & Hall (1970), 140: letter of Vernon to Oldenburg, 25 August 1670.
33. Danjon & Couder (1935), 645-6.
34. Huygens (1893), 117: letter of Moray to Huygens, 13 September 1664. Moray noted that for planetary work it was stopped down to $3\frac{1}{2}$", but Oldenburg later mentioned it as operating at about $2\frac{1}{4}$": Hall & Hall (1966), 306.

35. The discussion below of lens grinding for objectives is based on Daumas (1953), 34-6, supplemented by the parts of Smith (1738), 281-301, that related to early lens production, and by Bedini (1966).

36. Bedini (1966), 690.

37. Daumas (1953), 37.

38. Ibid, 151.

39. Kepler (1611), see King (1955), 44.

40. Descartes (1637), see King (1955), 48.

41. Van Helden (1974), 46.

42. Van Helden (1977), 26.

43. Van Helden (1974), 46 n 42.

44. Bedini (1967). For a correction and comment on terminology see Van Helden (1974), n44 & n46.

45. See Rigaud (1832).

46. Daumas (1953), 36, 72.

47. Turnbull (1959), 92: letter of Newton to Oldenburg, 6 February 1671/2.

48. Hall (1955).

49. Bennett (1975), 161. This paragraph is based on Dr Bennett's article, which is a condensation of aspects of his 1974 Cambridge University dissertation.

50. Hall & Hall (1966), 478 n4, 584, 641.

51. Taylor (1954), 256; Court & von Rohr (1929), 255; Gunther (1930), 297.

52. Hall & Hall (1971), 73, 537: translation of letters of Oldenburg to Huygens, 1 January and 12 February 1671/2.

53. Gunther (1930), 415, 666.

54. Hall & Hall (1971), 521: translation of letter of Huygens to Oldenburg, 3 February 1671/2.
55. Hall & Hall (1966), 394: translation of letter of Hevelius to Oldenburg, 22 May 1664/5.
56. For example Hall & Hall (1971), 475: translation of letter of Oldenburg to Ott, 15 January 1671/2.
57. This is discussed below in the section 'Reaction to Newton's Telescope'.

CHAPTER 3 ISAAC NEWTON AND THE EARLIEST REFLECTING TELESCOPES

3.1 EARLY PROPOSALS FOR REFLECTING TELESCOPES

The understanding of the action of mirrors and lenses has a long history which recedes into classical antiquity. Among the principal influences in the geometrical study of their properties was the optical work of the Arab mathematician Ibn al-Haytham (965-c.1040), who had incorporated experiments aimed at developing a working theory of refraction and reflection. His work was latinized in the 12th or 13th century, and together with that of a later Polish disciple Witelo (c.1230-post c.1275), circulated in manuscript form in succeeding centuries, but became widely known in printed editions of the 16th century.(1) In particular the combined edition of their work published in 1572 served as the standard textbook on optics until well into the following century.(2)

Practical optics had developed to the extent that by the beginning of the 16th century concave and convex mirrors were to be found in domestic use to produce enlarged or diminished images.(3) In the latter part of the century spectacles, which were initially produced only with convex lenses to correct for presbyopic long-sight, were becoming available with concave lenses, which were more difficult to construct, for the correction of short-sight.(4) It was not until the following century that lenses began to play a part in formal optics. In the period before this however the confluence of theoretical and experimental science has been seen in the philosophy of Rennaissance scholars concerned in the revival of interest in magic and the occult. A. van Helden has found this view consistent with the earliest accounts of the powers of lenses and mirrors in the writings of such natural philosophers as John Dee and Giovanbaptista Della Porta.(5) A limited number of references to the apparent possibilities of mirrors and lenses in the late 16th century have been examined repeatedly for evidence of the early construction of telescopes, the most recent and persuasive account being that of van Helden.[6]

The promotion of practical mathematics, including surveying, navigation and ballistics, made a slow start in England, compared with progress in continental Europe. One of the earliest exponents was Leonard Digges (c.1520-59?) who published a number of pioneering works aimed at bringing the mathematical arts and the use of mathematical instruments within the reach of the master-craftsman and artisan.[7] He shared his mathematical interests, together with his conviction of the importance of astrology and occult studies, with the more renowned John Dee (1527-1608), who became a close friend. Influenced by the earlier optical writings of the 13th-century Franciscan friar Roger Bacon, both Digges and Dee experimented with the effects of lenses and mirrors and produced perspective and burning glasses. Digges' work is known from a treatise written before 1556 but edited and published after his death by his son Thomas, in which two somewhat obscurely worded passages (one added by Thomas) refer to perspective instruments. Although it seems most probable that he did not combine lenses to produce a refracting telescope, it has been argued that he may have used mirrors in conjunction with a lens to form a reflecting telescope:

> "Marveilous are the conclusions that may be performed by glasses concave and convex of Circulare and parabolicall formes, using for multiplication of beames sometime the aide of Glasses transparent, which by fraction should unite or dissipate the images or figures presented by the reflection of other. By these kinde of Glasses or rather frames of them, placed in due Angles, yee may not onely set out the proportion of a whole region ... but also augment and dilate any parcell thereof ... But of these conclusions I minde not here more to intreate, having at large in a volume by it selfe opened the miraculous effects of perspective glasses." (8)

The volume mentioned at the end of this extract was never published. Some authors have interpreted this passage as describing an instrument that might be termed a reflecting telescope(9): van Helden however dismisses the description as vague and obscure and the 'marvellous conclusions' as fanciful speculation.(10)

After the early death of his father, Thomas Digges (1546?-95) studied under Dee and remained a close associate, coming to be regarded as a master of experimental science. Both Thomas Digges and Dee apparently continued to experiment with optical glasses, since they were appealed to both for the breadth of their knowledge and experience, and for their resources for experimentation, in a manuscript account of optical glasses drawn up by William Bourne (fl. 1565-1588). This undated 'Treatise on the Properties and Qualities of Glasses for Optical Purposes' had been requested by Sir William Cecil, Lord Burghley, Elizabeth's chief minister, in the late 1580s.(11) In it, Bourne described the manufacture and use of various types of back-silvered mirror and lens, and his account of the action of convex lenses clearly reveals his familiarity with them. This personal experience apparently did not extend to combinations of lenses and mirrors, but he felt able to express his belief that a concave mirror and convex lens could be combined so that

> "the glass that ys grounde, beynge of very cleare stuffe, and of good largenes, and placed so, that the beame dothe come thorowe, and so reseaved into a very large concave lookinge glass, That yt will shewe the thinge of a marvellous largenes, in manner uncredable to bee beleeved of the common people." (12)

After a confused account of how the effect could be compounded by adding yet further components, he concluded:

> "so that those things that Mr. Thomas Digges hathe written that his father hathe done, may bee accomplisshed very well, withowte any dowbte of the matter: But that the greatest impediment ys, that yow can not beholde, and see, but the smaller quantity at a tyme." (13)

Clay and Court concluded from this that Bourne had appreciated the limited field of view of such an instrument, and must therefore have looked through one or had the appearance of the image explained to him by Digges.[14] Van Helden more reasonably suggests that Bourne was merely referring directly to the passage in Pantometria already cited, with which it has a close similarity. He supports his contention that Bourne had not tried to combine optical components by noting that a magnifying effect would only be obtained in the instrument described in the first extract above if a small (i.e. short focal length) concave mirror and not a "very large" one were used in conjunction with an object glass. He suggests in fact that Bourne was guided by the naive principle that magnifying effect was additive, and thus "if one 'glass' magnifies, two will magnify more."[15]

Whether Digges, father or son, actually constructed a reflecting telescope, rather than a simple catoptric device for distant seeing, seems at best highly doubtful. Nor can it yet be said what influence, if any, their writing had on later experiments. More substantial claims can however be made for early 17th-century Italian and French attempts. These have received scant attention in accounts of the development of the telescope, but have recently been examined by P.E. Ariotti, who has been concerned principally with the work of Bonaventura Cavalieri.[16]

News of the discovery of the refracting telescope spread rapidly across Europe in the months after October 1608.[17] The earliest instruments were comparatively easy to realise as they used the standard optical components of the spectacle maker. Producing lenses of a quality sufficient for instruments with a significant magnification was a different matter. The most successful of the first experimenters was undoubtedly Galileo, whose persistent efforts led to an instrument with which he was able to discover the moon system of Jupiter. The publication of his findings in 1610 immediately raised the telescope to a position of prominence.[18] The development of telescope optics continued to be a subject of keen interest in Galileo's circle. Not unnaturally this interest had extended to reflecting optics also, and Galileo's close friend Gian Francesco Sagredo (1571-1620) projected a catoptric telescope, but apparently without success.[19] More is known of an attempt claimed to have been made about this time by Niccoló Zucchi (1586-1670), the Jesuit professor of mathematics at the Collegio Romano, who later wrote that he had experimented with the use of an objective mirror in 1616.[20] The telescope employed a bronze concave mirror and a concave glass eye-piece, and from the brief description of the instrument it appears that it was a front-view telescope of the type later employed by William Herschel. It did not match Zucchi's expectations and he reverted to refracting telescopes, only making his work known in 1652.[21]

In 1626 Galileo was in correspondence with another friend and scientific associate, Cesare Marsili, who had sent him news of two optical workers of Bologna who had produced concave mirrors. One of these, Cesare Caravaggi, had recently died, but his colleague, "a certain Giovanni", was heir to his techniques. In addition to making burning mirrors:

> "These two men boasted, and the latter still does ... to be able to make a mirror which by reflection can, and indeed does produce the effect of the telescope. But although the deceased was my very close friend, I was neither allowed to see the mirror ... nor the effect." (22)

The news was received with great interest by Galileo, and in their subsequent correspondence the two men speculated about the operation of the instrument, agreeing that a steel mirror would require to be used in conjunction with an eyelens before it could achieve the effect of a telescope. If a reflecting telescope was produced - and Marsili cited independent evidence that it had been - then it has been proposed that the invention was lost because its operation was kept a jealously guarded secret from those such as Marsili who could have understood and therefore copied it.(23) Aside from this, we can conclude, as A.J. Turner has stressed, that the concept and practical problems of reflecting telescopes were known to Galileo's mathematical circle in 1626.(24)

A further facet of this debate is provided by the work of the mathematician Bonaventura Cavalieri (c.1598-1647).(25) Cavalieri had studied at Pisa under Benedetto Castelli, a principal follower of Galileo, and corresponded with both. Partly through the influence of Marsili he was appointed professor of mathematics in Bologna in 1629, and it was here that he published <u>Lo Specchio Ustoria ...</u> [The Burning Mirror] at Marsili's urging in 1632.(26) The book treats work undertaken "several years" beforehand, and in it Cavalieri claimed to remedy deficiencies in the treatment by Witelo, Bacon and others of the properties of mirrors by providing a systematic study of the whole range of conic section reflecting surfaces. Although the stated object of the <u>Specchio</u> was the resolution of the problem of the burning mirror allegedly used by Archimedes, the book ranged over a number of related topics including the design of reflecting telescopes. Ariotti proposes that it is the activities of Carravaggi and his colleague, also in Bologna, that were being referred to when Cavalieri mentioned that he had "heard more than once of the search by some people for a way of combining glasses that would produce the effect of the telescope ...".(27)

The main text is a systematic analysis of reflecting surfaces internal and external to conic sections, and their effect on incident parallel light or on light converging to and diverging from a mathematical focus of the conic curve. This allowed him to develop conditions for the combination of reflecting surfaces to focus, direct and manipulate beams of light, or indeed of sound or heat. In his illustration of the construction of such compound burning mirrors, and in his admission not only that spherical mirrors could be used for them instead of parabolic ones, but also that concave lenses could replace the small convex secondary mirrors, Cavalieri laid a theoretical foundation for the realisation of reflecting telescopes.

Cavalieri had certainly given consideration to the construction for such a telescope which would be formed of "a combination of these mirrors or of mirrors and lenses although the facility of producing the spherical figure will make it so that we will use it rather than the others."(28) In particular, Cavalieri described, but did not illustrate, a design employing a concave mirror, a concave lens and an "interposed" flat mirror. From a careful translation and analysis of Cavalieri's account, and of his comments to Galileo on the use of such a flat mirror in a burning mirror, Ariotti has concluded that Cavalieri's design anticipated that of Newton's later telescope. In his interpretation, the small flat mirror is placed diagonally on the axis of the main mirror, directing the light into the concave lens placed at the side of the tube. Ariotti has been able to eliminate other possible combinations and to deduce that focusing was to be achieved by moving the flat mirror and lens together along the tube's axis.(29) Cavalieri described his design as follows:

"I thought that such could be accomplished by placing an ocular at one side and a small concave mirror at the other. For, if we take these two glasses and interpose a flat mirror which faces us and which can be brought nearer or farther away as it is needed to see the image distinctly in the small concave mirror (and we shall see both the one and the other in the flat mirror) the telescopic effect will be achieved." (30)

Cavalieri's use not only of intact but also perforated primary mirrors indicates, at least in the context of compound burning mirrors and similar devices, that he had anticipated the Cassegrain and possibly also the Gregorian form of combination. In addition, Ariotti has shown from Cavalieri's correspondence with Galileo that he was also considering the front view form of Zucchi.(31)

In accounting for the fact that Cavalieri apparently did not construct a reflecting telescope, Ariotti points to the serious difficulties of grinding concave mirrors: Cavalieri had tried to make a parabolic mirror some years later, but neither he nor a local artisan was successful. It is clear however that Cavalieri did not really believe that the reflecting telescope was a practical proposition, and he had no sooner raised the idea in his book than he was condemning it:

"... I have taken this opportunity to mention such [an idea] but only as something whimsical, to give satisfaction, in other words, to those frivolous people who crave for cake instead of bread. For in my view they will never match the excellence of the refracting telescope either by combinations of mirrors or by the addition of lenses as anyone who wishes to try will, I believe, find out." (32)

Better known than the work of Cavalieri are the designs of the French Minim friar and natural philosopher, Marin Mersenne (1588-1648), published in a number of his copious works around 1640.(33) Mersenne played a significant role in the development and organisation of Parisian science and had a wide correspondence. He maintained an active interest in Galileo's research, and of his own broad scientific interests he made particular contributions to the study of acoustics. It was in relation to an acoustic device that the telescope designs were proposed, and although they could also be used optically as burning mirrors for lighting fires "it will be more to the point to use such an invention in making telescopes."(34) In two of the three suggested schemes the large parabolic section primary mirror is pierced at the centre, and light parallel to the mirror's axis is brought to a focus but intercepted by a smaller parabolic section secondary mirror, cofocal and coaxial with the primary, which then directs the light as a parallel beam back through the centre of the main mirror to the target or the observer's eye. The two designs employed either a concave or a convex paraboloid and may be considered as germinal forms of the Gregorian and Cassegrain telescopes. The third scheme is of no practical importance. Although Cavalieri's Specchio Ustoria does not appear to have been widely read, Ariotti has stressed that Mersenne was familiar with it and specifically acknowledged its influence and priority elsewhere in his work.(35) Presumably therefore we must admit Mersenne's debt to Cavalieri in the design of these telescopes.

Descartes was not impressed with Mersenne's proposal, and he insisted in 1639 that the reflecting telescope could only be inferior to the refractor. His first objection, that the eye could not be placed close enough to the mirror, was certainly well founded. Since the rays were made parallel again at the secondary, the angular size of the object viewed was subtended at the focus of the secondary: theoretically therefore the optimum position for the eye was as close behind this focus as possible, but if it was well separated from it (as in Mersenne's designs) the field of view would be impossibly restricted. Three further objections concerned the exclusion of stray light, the problem of obtaining more than a token magnification, and the low efficiency of reflection. Although these were of less consequence than the first, they nonetheless raised real difficulties.[36]

No doubt in the light of the progress then being made in the performance of refractors, it seemed rather pointless to pursue this less than promising instrument with all its associated technical problems, and certainly there is no indication that this was attempted. When the reflecting telescope did at last become a practical proposition, Mersenne's contribution was not entirely forgotten, and an early instrument of Robert Hooke's was described as performing "by a way propounded by Mersennus ... but never actually done before."[37]

Notes and References

1. Lindberg (1976) has concluded that al-Haytham's Optics or De aspectibus was the principal influence on Witelo, and that the latter's analysis of paraboloidal mirrors was drawn from the anonymous De speculis comburentibus, now attributed to al-Haytham. Witelo's Perspectiva was published as the Optica in Nuremberg in 1535 and 1551. Al-Haytham's Optics was first published by Risner in Basel in 1572 in a collective volume containing Witelo's work.
2. Risner (1572); Lindberg (1976), 461.
3. A mounted convex mirror is shown in a miniature from a Flemish manuscript of c.1480 illustrated in Edwards (1924-7) II, 310.
4. Van Helden (1975), 259. Ilardi (1976) has demonstrated that concave lenses were available in quantity in Florence as early as 1462, and van Helden (1977) has discussed their gradual spread across Europe in response to a low level of demand from myopes.
5. Ibid, 12.
6. Ibid, 12-16. See also Baxandall (1922-3), Gunther (1923), Clay & Court (1932), Danjon & Couder (1935), Johnson (1937), King (1955), etc.
7. The account of Leonard and Thomas Digges is based on that in Taylor (1954) using the dating adopted in Easton (1970).
8. Digges (1571), 28.
9. The claim is made most clearly by Gunther (1923), 289-91, but is followed by Clay & Court (1932), 7, and King (1955), 29. King cites only the modern rendering from Digges printed by Gunther.

10. Van Helden (1977), 14. He points out that the mention of a dissipating glass is the only 16th-century reference to a concave lens known to him in the English literature.

11. William Bourne 'A treatise on the properties and qualities of glasses for optical purposes, according to the making, polishing, and grinding of them': Brit. Mus. MS Lansdowne 121, printed in Halliwell (1839), 32-47.

12. Ibid, 46.

13. Idem.

14. Clay & Court (1932), 7.

15. Van Helden (1977), 14.

16. Ariotti (1975). A summary is given in Turner (1977), 72.

17. Van Helden (1977), 26-7, 40-52.

18. Galileo (1610).

19. Ariotti (1975), 305; Danjon & Couder (1935), 605.

20. Ibid, 608.

21. Zucchi (1652), see Danjon & Couder (1935), 607.

22. Ariotti (1975), 306.

23. Ibid, 307.

24. Turner (1977), 72.

25. The discussion below is closely based on Ariotti's analysis of Cavalieri's optics: Ariotti (1975). See also brief extracts concerning his telescope design in Danjon & Couder (1935), 606-7.

26. Cavalieri (1632).

27. Ariotti (1975), 314.

28. Idem.

29. Ibid, 316.

30. Ibid, 314, 316.

31. _Ibid_, 317.

32. _Ibid_, 320.

33. Initially in Mersenne (1636) I, 61-2. Reproduced e.g. in Danjon & Couder (1935), 606-7 and Ariotti (1975), 318.

34. Danjon & Couder (1935), 608; Ariotti (1975), 318.

35. _Ibid_, 317, 319.

36. _Ibid_, 320; Danjon & Couder (1935), 609.

37. Roy. Soc. MS Journal Book, meeting of 5 February 1673/4.

3.2 JAMES GREGORY AND HIS REFLECTING TELESCOPE

The concept of using reflecting optics for constructing a telescope had clearly been appreciated in early 17th-century continental Europe, and there are grounds for believing that instruments may have been constructed. These early practical attempts however, although of historical interest in terms of priority for the invention, appear to have passed unnoticed, and the stimulus they might otherwise have provided for further development was lost. By contrast, the realisation of a practical reflecting telescope in Britain in the 1660s may be seen as the first link in a developmental chain of influence which ultimately led to the instrument's firm establishment and its dominant role in observational astronomy in the 18th century. Thus in the context of the practical development of the reflecting telescope, and of the international reputation acquired by the British workshops, the early British instruments have a significance which is more certain than that of their Continental precursors.

The reflecting telescope reached a high standard of excellence in the hands of the Scots optical worker James Short (1710-68), who settled in London in 1738 and made a comfortable fortune as an "optician solely for reflecting telescopes".(1) It is perhaps appropriate that his skill should have made the instrument such a conspicuous success, since it had been a fellow countryman, the mathematician James Gregory (1638-75), who had described and constructed the first reflecting telescope in Britain in the preceeding century.

James Gregory was born the youngest son of an Aberdeenshire minister, and through his mother he was descended from the scholarly Andersons.(2) The family and their descendents displayed remarkable academic ability, and over 6 generations they occupied more than twenty chairs at the Scottish universities and at Oxford. James Gregory himself came to hold the chair of mathematics at both St. Andrews and Edinburgh and was one of the most important mathematicians to work on the development of fluxional calculus. Four years Newton's senior, Gregory has been described as "the only one of Newton's British contemporaries who could match him in mathematical breadth and profundity".(3) However, his comparative isolation from his mathematical contemporaries, his reluctance to publish his work, and finally his early death, all conspired to restrict his contribution to mathematics.

Gregory's mathematical inclinations were recognised by his elder brother David, who was himself an enthusiastic amateur mathematician. David sent him to Aberdeen for his formal education, and after his graduation from Marischal College, he encouraged him to continue his studies. Gregory's first publication, his Optica Promota of 1663(4), is a gathering of these early researches in geometrical optics and astronomy and is remarkable for its inclusion of a design for a practical reflecting telescope. The volume was based on his reading of al-Haytham, Witelo, Kircher and others, and in the preface he described how "moved by a certain youthful ardour ... I have girded myself with these optical speculations, chief among which is the demonstration of the telescope."(5)

The main text of the Optica Promota has been described by Whiteside as "interesting more for its revelations of the inadequacies of his early scientific training than for its technical novelties."(6) At Aberdeen Gregory did not have access to a sufficiently comprehensive library, there being a "scarcity of new mathematical books in the Aberdeen Library".(7) Although he received encouragement from his brother David, acknowledged in the preface, he was not in contact with any practising mathematician. Whiteside has noted that Gregory made good use of those optical and astronomical works that were available to him, notably Risner's 1572 edition of al-Haytham and Witelo(8), but was hampered by an ignorance of the contents of Descartes' Dioptrique of 1637 in which the sine law for refraction was first publicly announced.

The 59 optical propositions of Gregory's book deal with catoptrics and dioptrics, that is reflecting and refracting optics. These are followed by the description of a reflecting telescope appended in an 'Epilogus', and finally there are 31 astronomical propositions. In the first of the optical propositions Gregory developed an intuitive demonstration of a law of refraction, equivalent to the sine law, allowing parallel light incident on a central conic surface to be refracted to a focus. He then demonstrated an experimental agreement with the tables of refraction published by Witelo and Kircher; thus "the mathematics and more subtle observations confirm this most beautiful speculation of dioptrics."(9)

The optical propositions that follow discuss the formation and disposition of images in conic section mirrors and refracting surfaces and lenses, and Gregory has been concerned to stress the parallelism of reflection and refraction. A group of propositions(10) of particular interest demonstrate that the images formed by concave elliptic and convex hyperbolic section mirrors of small plane objects, normal to the axis of the mirror and placed at a focus, are themselves approximately plane: similarly the images formed of infinitely distant objects of small angular size by parabolic section mirrors and conoid refracting surfaces (and hence lenses) are also approximately

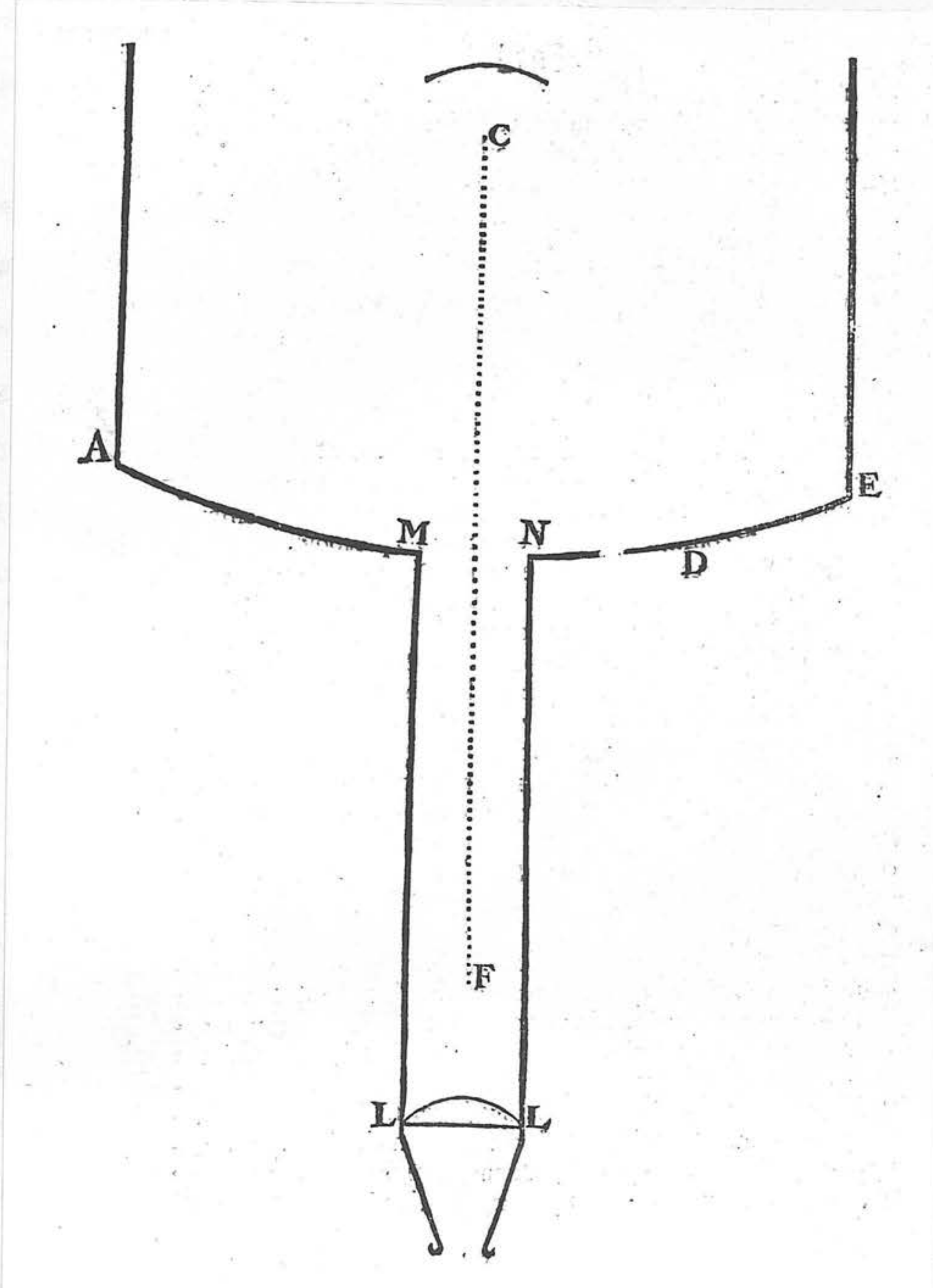

Fig.1. James Gregory's reflecting telescope: the optical scheme as published in his Optica Promota of 1663.

plane. These results are of course prerequisites for the effective coupling of any such imaging elements to form a telescope, and they represent a departure from those earlier accounts restricted to imaging on the axis of the optical components.

Gregory's telescope proposal is described in an Epilogue placed after the optical propositions. He introduced it by describing three classes of telescope. The first is purely dioptric, and suffers from a number of disadvantages: refracting telescopes had grown too long to be manageable, and the image quality was poor because of the number and quality of the glasses. The second is purely catoptric, employing a system of mirrors to avoid the defects of the first, but losing too much light at each reflection. However, in a third class of instrument the optical system was a mixture of mirrors and lenses (later to be dubbed 'catadioptric') and Gregory claimed this could be devised so as to avoid the disadvantages of the other two classes.(11)

The telescope he proposed had a concave parabolic section mirror "exquisitely polished" and with a concentric circular aperture. Beyond the focus of this speculum was placed "a small elliptic concave mirror, having a common axis and common focus with the parabolic concave mirror".(12) Despite the technical difficulties of producing conic section surfaces, Gregory was convinced that they were ultimately necessary:

> "Concerning the mechanics of these mirrors and lenses which have been vainly attempted by others, I being less versed in mechanics make no claim: however I boldly assert that the perfection of optics is sought in vain in spherical lenses and mirrors." (13)

Gregory did in fact commission such an instrument to be made and in view of the criticism later levelled at the attempt, and particularly at the use made of spherical surfaces, it is important to note that

Gregory did not insist on conic sections. Although the optical propositions of the book had been derived for conic sections "Yet, if anyone wishes, he will be able to apply to spheres the main propositions; although not so perfectly".(14) Gregory's justification, given in the specific context of mirrors for reflecting telescopes, was that a reflecting surface was represented by portions of spheres with the same local radii of curvature, and although these spheres "cannot altogether concur with" each other, yet if they can "at least as far as the sense is concerned" then the approximation is justified. If conic section surfaces could not be achieved, but only spherical ones, then it remained true that the use of mirrors was still preferable to the use of lenses:

> "Nevertheless if conic lenses and mirrors are not available, it will be better to use spherical portions in place of ellipsoids and parabolic conoids in catoptrics than it would be to use them in place of hyperbolic conoids in dioptrics since the latter agree with spherical portions less well." (15)

In 1662 Gregory, conscious of his restricted scientific opportunities in Aberdeen, travelled to London, bringing with him for publication the manuscript of the Optica Promota.(16) During his stay in London, in which he saw his work through the press, Gregory made the acquaintance of his fellow countryman Sir Robert Moray (1608?-1673). A statesman of great influence, Moray was also a central figure in the then young Royal Society of London, and through his correspondence with Christiaan Huygens was a principal link between the London and Continental scientific communities. Gregory intended to continue his studies abroad, and Moray gave him an introduction to Huygens, who was to spend the Spring of 1663 in Paris. Unfortunately when Gregory reached Paris, probably at the end of February or beginning of March, he found that Huygens had not yet arrived, and he had to be content to leave a copy of his book.(17) Huygens duly acknowledged this to Moray, but his opinion is not known.[18]

The object of Gregory's journey was to be Padua in Italy, which then boasted the most renowned University in Europe. Stefano degli Angeli, a pupil of Cavalieri and Torricelli had just been appointed to the vacant mathematics chair and Gregory studied geometry, mechanics and astronomy under him until 1667.[19] In the two mathematical works published by Gregory towards the end of his Italian stay, Whiteside finds that "a sheen of confidence gleams through Gregory's work", and from his exposure to the intellectual centre of Italian science "he at last emerges fully aware of his hitherto latent mathematical powers."[20] The Vera circuli et hyperbolae quadratura, in which he developed algebraic sequences for determining the area of central conics by convergent series, had been published in Padua by October 1667.[21] The work was reprinted in Padua (for the State of Venice) in early 1668, and issued together with Gregory's Geometriae pars universalis, which is concerned with problems of geometrical transformation.

Gregory returned to London in late Spring 1668 to find that the Vera circuli had been enthusiastically received and that he was in demand for his recent contact with Italian science. He was elected to the Royal Society in June, and remained in London for some months before moving to St. Andrews to take up the new chair of mathematics, thought to have been secured for him by Sir Robert Moray. After his departure for St. Andrews, and his move to Edinburgh a few years later, Gregory's sole contact with current mathematical developments was through his London correspondent John Collins (1625-83), a mathematician who held a variety of Government accountancy posts. Through the Royal Society, and also on his own account, Collins conducted a wide correspondence with the principal mathematicians of the day, both at home and abroad, encouraging the interchange of mathematical news and playing a significant part in the promotion of mathematical publishing.(22) Collins' early contacts with Gregory had been concerned largely with the availability of scientific books in Italy, and it had been Collins who reviewed Gregory's work so favourably in London and promoted him in the Royal Society. Latterly Collins was the intermediary between Gregory and Newton when the merits of their respective designs for reflecting telescopes was under discussion.

During his first visit to London in 1662-3 Gregory attempted to have his proposal for a reflecting telescope put into practice, and the work was placed in the hands of Richard Reeves of Long Acre, who at the time was the most accomplished optical worker in the capital. The popular story is that Gregory was introduced to Reeves by Collins, with whom he had struck up a close friendship.(23) On the whole, this seems unlikely. The earliest extant correspondence between Collins and Gregory dates only from early 1668, and on that occasion Collins reminded him that "it was once my good hap to meet with you in an alehouse, or in Sion College", suggesting that their acquaintance was slight and their correspondence not yet established.(24) Nor did Collins receive one of the 150 copies of the first impression of the Vera quadratura distributed by Gregory in Autumn 1667; instead he was lent one by Samuel Thomson, the London stationer who had published Gregory's Optica Promota. Collins certainly maintained contacts with a number of the stationers, and several mentions of Thomson in the early correspondence suggests that Thomson had been the initial link between the two mathematicians. In late 1668 Collins wrote to Gregory at St. Andrews that "your acquaintance Mr Samuell Thompson is dead", and it is clear that Thomson was at the time supplying Gregory with copies of the Philosophical Transactions.(25) Collins' most likely contact with optical apparatus would have been through the Royal Society, to which he was elected only in 1667. However, if Collins had been the means of introducing Gregory to Reeves, one would expect him to have made some contribution to the later correspondence about the instrument that Reeves constructed, but he does not.

A much more likely person to have persuaded Reeves to try the experiment is Sir Robert Moray, particularly as the work was undertaken shortly before Gregory went abroad and at a time when Moray is known to have been taking an interest in him.(26) Moray was certainly personally acquainted with Reeves through the latter's work for Sir Paul Neile and the Royal Society.

Richard Reeves is first recorded as making lenses and telescopes for John Pell about 1640.(27) It may well have been Reeves who was working a few years later for Jonathon Goddard, who was a member of an informal group of physicians and mathematicians whose meetings, John Wallis recalled, were

> "held sometimes at Dr. Goddards lodgings in Woodstreet (or some convenient place near) on occasion of his keeping an Operator in his house, for grinding Glasses for Telescopes & Microscopes". (28)

Reeves was closely associated with the efforts of Goddard's colleagues Sir Paul Neile and Christopher Wren to develop refracting telescopes of increasingly long focal length. Robert Hooke subsequently recounted that this work, continued under the Royal Society's auspices, had been undertaken by

> "Sir Paul Neile, Sir Christopher Wren and Dr. Goddard, who instructed and employed Mr. Reives in the manual operation; and by that means, it was carried to the perfection of making object-glasses of 60 and 70 foot long, very good". (29)

Wren was inaugurated as professor of astronomy at Gresham College, London, in 1657. His main astronomical associates were Goddard, then professor of physic at Gresham, and Neile - both of them actively concerned in the practical optics of telescopes.[30] Neile and Wren erected a 35 foot telescope in the grounds at Gresham in 1658. It was subsequently presented by Neile to the Royal Society, which grew in 1660 from the informal scientific group that was in the habit of meeting in the College. Charles II was greatly impressed with the telescope, and Neile was instructed to have another made for use at Whitehall.[31] Sir Robert Moray, who (acting to some extent with Neile) was the principal link between the Society and its Royal patron, was present in May 1661 when Charles viewed the new instrument.[32] In 1664 Neile presented the Society with a 50 foot objective, constructed at about the same time as the earlier 35 foot instrument.[33] Wren said that Neile had "hired the best workmen" to make his instruments, supervising the work himself.[34] This, and the encouragement given to Neile by the Society in 1661 "to continue his employment of the artificer for making glasses for perspectives", presumably refers to Reeves.[35] Certainly, Reeves was the maker of a long telescope made to Neile's direction which was in Pope Alexander VII's possession in 1660.[36] In 1664 Hooke was using a telescope of over 60 foot by Reeves and in the following year a Royal Society Committee (of which Moray was a member) examined objectives by Reeves to compare them with Campani's.[37]

Although Reeves was to be eclipsed in the 1670s by his former associate Christopher Cock, his reputation in the early 1660s was unchallenged. Under the patronage and tutelage of the astronomers of the early Royal Society he had developed new skills that enabled him to satisfy demanding commissions, and his position in the scientific community may be gauged from the fact that Christiaan Huygens and Thomas Streete observed the 1661 transit of Mercury from Reeves' shop with one of his telescopes.(38)

The trial carried out by Reeves for Gregory in 1663 appears to have been brief and, from the instrument-maker's point of view at least, fairly inconclusive. It would probably have been forgotten completely had not Reeves been working with Robert Hooke developing the apparatus used in Hooke's microscopical researches, subsequently published in his Micrographia of 1665.(39) Hooke was able to make some trials with the mirrors which had been ground for Gregory and which had clearly remained in Reeves' hands, and these may well have been the inspiration for other reflecting instruments he constructed, and in particular for reflecting microscopes, with which he had some success.(40) These trials however only came to light in early 1672 when Hooke was asked by the Royal Society to assess Newton's paper announcing his new theory of light and colour. Only now, to demonstrate that Newton had not been the first to grind concave telescope mirrors, did Hooke describe how he had experimented (unsuccessfully) with

> "one of six foot Radius, which about 7 or 8 years since Mr Reive made for Mr Gregory wth wch I made severall tryalls" (41)

Hooke's critique was sent to Newton; and when Newton in turn was asked to comment on a new proposal for the Royal Society - the telescope design of Cassegrain - he pointed to the similarities of Cassegrain's and Gregory's designs, and drew support from the apparent failure of both Gregory and Hooke for his contention that neither was practical, whereas of course his own design was eminently so.[42] The confusion centred on whether the failure was due to attempting the theoretically required non-spherical surfaces, and on whether Gregory's experiment had been a serious attempt to produce a finished instrument. Gregory felt obliged to enter the discussion in late 1672 to protect his proposal, which was being associated with Cassegrain's in Newton's cutting criticisms, and in the course of an extended correspondence a number of valuable details emerged.

Newton had initially assumed that the mirrors had been intended to have parabolic and elliptic surfaces. He had based this on Hooke's claimed difficulty in generating a parabolic section which had discouraged him from making further experiments[43], and also on Gregory's statement in his Optica Promota, quoted above, that non-spherical surfaces had been 'attempted in vain'. However, for the book to have been printed in time for Gregory's departure, the work by Reeves must have been done after Gregory's comment was printed, and Gregory in fact closed the discussion by noting:

> "I think no thing can be inferred concerning the tryal of my telescope from my assertione; seing the trial was after that assertion: but Mr Newton could not be supposed to know this." (44)

Although to some extent Newton and Gregory remained at cross purposes, it seems clear from Gregory's comments that the 'vain attempts by others' at non-spherical surfaces were reported efforts, unconnected with his own work. In particular, he was not saying that other workers (such as Reeves), who had the skill that he lacked, had failed to produce such surfaces for him. However, for him to have been aware that such attempts had been made suggests that this comment was added to the text of his book after he arrived in London: early discussion with Moray, or with Reeves himself, would quickly have informed Gregory of unsuccessful attempts (presumably those of Neile and Reeves) to grind non-spherical surfaces. There is a further indication of a modification to the text: in the preface Gregory mentions Descartes' work of which he has now heard, but which he has not yet seen.[45] One might indeed postulate that the possibility of actually constructing a telescope did not occur to Gregory until he reached London, and that the Epilogus, which in several ways stands apart from the rest of the text, was added only after his arrival and immediately before the book was printed.

It seems clear that before events had taken a practical turn he was persuaded that parabolic surfaces were not readily obtainable, and had lowered his sights to spherical surfaces, which, he could demonstrate, were a good approximation. He certainly made a definite distinction in a subsequent letter between the 'vain attempts' at non-spherical surfaces and "my experiment with Mr Rives".[46] The experiment took the form of an attempt to grind and polish a large spherical concave with a radius of about 6 feet and therefore with a focal length of 3 feet, together with spherical secondary mirrors. The commission was not as unusual as might be supposed. Reeves required to fashion accurate spherically concave metal tools in which to polish objective lenses, and Gregory's proposal in effect called for a suitable 'tool' to be polished to form the mirror.[47] Reeves, who at the time was still being assisted by Christopher Cock, ground the metal on a convex tool but was unable to obtain a suitable polish.[48] This lack of polish (described by Gregory as a "great defect in the figure") would he believed counteract the advantages which he had ascribed to reflecting telescopes, and so as his time in London was now short he made only hasty trials.(49) Indeed it appears that it was Gregory's impatience to be away that curtailed the experiment: Reeves and Cock believed they would have better success with a smaller diameter mirror, although presumably of the same focal length, "for they undertook indeed to polish a less speculum to me upon the tool".(50) Gregory, however, had "thought it not worth the pains to trouble myself anie further with it", but secondary mirrors had been constructed and combined with the primary with sufficient success to see "transient views of the object".(51) Probably they would have performed better had Gregory mounted them in a proper tube, but he had been "so possessed with the fancie of the defective figure, that I wold not be at the pains to fix everie thing in its due distance."(52) It is of interest to note that although Gregory's description of the telescope had shown a concave secondary in the combination later known as the Gregorian form, Gregory in fact made his trials "both with a little concave & convex speculum" so that he also produced a working demonstration of the Cassegrain form.(53)

The reputation of Gregory's telescope has suffered as much from his own writings as those of Newton and Hooke. In particular, seen against the ideal requirements of his published design, the Reeves attempt was a failure. However, given that Gregory appreciated that spherical mirrors provided a satisfactory approximation for practical purposes, and indeed that he claimed that they would be better than spherical lenses, then an attempt that aimed to produce only spherical surfaces was perfectly reasonable. In what he set out to do, namely to demonstrate his proposal using spherical surfaces, Gregory achieved some success. It is certainly less than fair to claim as King has done that the mirrors "were worse than useless".[54] It is also misleading to suggest, as is normally done, that the main object was the generation of aspheric surfaces.[55] The importance of the instrument lies not in any partial success that may be claimed for it, but in the influence that it exerted on Hooke, the practical experience it afforded, and the stimulus it provided for subsequent discussion. The mirrors themselves are not known to have survived: possibly they were seized with the rest of Reeves' goods in 1664.[56]

Notes and References

1. Bryden (1970).
2. This account of Gregory is taken principally from Whiteside (1972), supplemented by Turnbull (1939).
3. Whiteside (1969), xiii.
4. Gregory (1663).
5. Turnbull (1939), 454, translating Gregory (1663), Preface $A3^r$.
6. Whiteside (1972), 525.
7. Gregory (1663), Preface $A3^r$.
8. The Marischal College Library copy of Risner (1572) was bequeathed in 1613, and is now in Aberdeen University Library. The latter also has a copy in its Gregory Collection, but whether this copy was in James Gregory's hands at this early period cannot be said. Personal communication from the Librarian, Aberdeen University Library, 29 Sept. 1980.
9. Turnbull (1939), 455, translating Gregory (1663), 13.
10. Gregory (1663): Propositions 37-43.
11. Ibid, 92-3. There is an intriguing possibility that Gregory may have encountered the designs by Mersenne for catoptric telescopes. These were published in a number of Mersenne's works including the Harmonica (Paris 1635), of which there was a copy in the Marischal College Library (but the provenance is unknown), and in the Cogitata physico-mathematica (Paris 1644), a copy of which was in the Gregory family collection (although again its acquisition date is unknown). Both are now in Aberdeen University Library. Personal communication from the Librarian, 29 Sept. 1980.

12. Gregory (1663), 93. Although Gregory described the mirrors as being co-focal, he had the secondary placed 'in' and not 'near' the focus of the primary. Turnbull (1939), 456, has noted that Gregory corrected this in his annotated copy, now in the Library at the University of St. Andrews.
13. Gregory (1663), 95.
14. Idem.
15. Idem. I am indebted to P. Gouldesbrough, Scottish Record Office, for checking my translation of this passage.
16. Whiteside (1972), 524.
17. Huygens' correspondence had misled Moray into thinking that he would leave for Paris earlier. When he heard at the end of March that Huygens was still at the Hague he wrote there to say that he had sent a letter to Paris by the hand of a young man who had instructions to leave it with Huygens' father (then resident in Paris) if Huygens had not yet arrived. This young man also had a present to give him of "a book of which he is the author, called Optica Promota, which treats Dioptrics and Astronomy, and of which I wish to say nothing so that you may reach a judgement in full": Huygens (1891), 330: letter of Moray to Huygens, 27 March 1663. The letter which Gregory was carrying was written by Moray on 19 February, so we may perhaps assume that the Optica Promota was published in February and that Gregory left for Paris towards the end of the month. Huygens arrived in Paris on 24 March.
18. Huygens' opinion was given in a letter which Moray did not receive. The book was acknowledged in another of 22 May, but his comments were reserved until he met Moray about 2 weeks later at the start of a stay in London: Huygens (1891), 351: letter of Huygens to Moray.

19. F. Enriques in Turnbull (1939), 465; Whiteside (1972), 524. The period of Gregory's study at Padua was apparently 1664–May 1667. He was associated while there with the Scot James Caddenhead, professor of logic and subsequently of philosophy.
20. Whiteside (1972), 526.
21. Huygens was sent a copy on 28 September 1667: Huygens (1895), 154.
22. For Collins see e.g. Whiteside (1971).
23. For example Stewart (1901), 28.
24. Turnbull (1939), 47: draft letter of Collins to Gregory. The omission of a passage from Isaac Barrow in the draft suggests the letter was dated after 6 March 1667/8, which was the date of Barrow's letter to Collins. The letter, which had an enclosure, gives the impression of being in part a repeat of an opening letter from Collins, and it was this earlier letter that Gregory answered on 16 March 1667/8 (Turnbull did not change the occasional 'new style' dates of manuscripts, see e.g. his letter 46), shortly before leaving Padua. Sion College was founded in London in 1623 as a college and almshouse, and had a substantial library.
25. <u>Ibid</u>, 55: letter of Collins to Gregory, 30 December 1668.
26. Turnbull (1959), 240: letter of Gregory to Collins, 23 September 1672.
27. Taylor (1954), 223.
28. Purver (1967), 166. The accuracy of Wallis' account has been qualified by Dr. Purver, but see Hill (1968) and Hall & Hall (1968).

29. Gunther (1930), 791, reprinting Hooke's 'Answer to some particular claims of Mons. Cassini's' from Derham (1726).
30. See, in particular, Bennett (1975).
31. Ibid, 156.
32. Hartley (1960), 160.
33. Bennett (1975), 161.
34. Van Helden (1968), 221, translating Wren's MS 'De Corpore Saturni'.
35. Hartley (1960), 159.
36. Huygens (1890), 45: letter of Guisny to Huygens, 15 March 1659/60.
37. Gunther (1930), 199: letter of Hooke to Boyle, 15 September 1664. ibid, 236, 238.
38. Huygens (1890), 271, 272 n5; Taylor (1954), 224. They missed the coronation of Charles II to observe the event. For a letter from Reeves with advice for the microscopist Henry Power on instruments suitable for observing the transit, together with a price list, see Court & von Rohr (1930-1), 121: Reeves anticipated that "several men of Art in town" would meet at his house to make observations.
39. Hooke (1665).
40. See the section 'Reaction to Newton's Telescope', ref 32.
41. The date must refer to Hooke's experiments, rather than the original work for Gregory, and it helps support the date claimed elsewhere by Hooke for his work on reflecting telescopes (Turnbull (1939), 223). This reference is apparently the cause of the confusion about the date of Gregory's departure for the Continent, which is sometimes claimed to have been in 1664: see e.g. Turnbull (1959), 115 n4, King (1955), 71. It may

also have led Professor Taylor to claim (incorrectly) that two telescopes were made, in 1663 and 1668: Taylor (1954), 246.

42. Turnbull (1959), 154: letter of Newton to Oldenburg, 4 May 1672.

43. Hooke's comment that the parabola was more difficult to describe than the hyperbola or ellipse related to geometrical constructions which were potentially useful in the grinding of conic surfaces: for example the property of generating a hyperboloid by a line (i.e. cutting edge) skew to the conoid's axis had been proposed by Wren. Hooke was preoccupied with the need to be able to produce the figure mechanically.

44. Turnbull (1959), 279: letter of Gregory to Collins, 13 May 1673. From the sense of this and of the letter it answers, the trial is that of Gregory and not Hooke. Gregory understood the 'trial' of the instrument as the attempt to put the design into practice and not subsequent experimentation with the components to test their effect. Newton initially presumed that Hooke had been involved in Gregory's original construction attempt, and therefore that careful efforts to produce non-spherical surfaces would have been made. Gregory, aware that Hooke had not been involved, made comments only on his own work, and began to resent Newton's pedantic interpretation of his earlier published comment which was having the effect of denigrating his instrument.

45. Gregory (1663), preface $A3^r$; Turnbull (1939), 454. Subsequent detailed study of Descartes after his arrival in London caused Gregory to revise his Optica Promota, but although part of the manuscript for this survives and Gregory at one time intended to publish it, yet it was never printed: ibid, 41-2, 55, 118, 262; Whiteside (1972), 526.

46. Turnbull (1959), 240: letter of Gregory to Collins, 23 September 1672. Newton later came to the conclusion that the trial had been only of spherical mirrors, but Gregory was not prepared to confirm this: ibid, 271, letter of Newton to Collins, 9 April 1673.

47. The radius of curvature was the same as that of the faces of the 6 foot objective lenses which Reeves was offering commercially at the time: Court & von Rohr (1930-1), 121.

48. Gregory provides the only evidence that Cock was working for Reeves at this period in his letter to Collins of 7 March 1672/3: Turnbull (1959), 259. By 1668 they were competing for a commission from Hevelius: Hall & Hall (1970), 48.

49. Turnbull (1959), 240: letter of Gregory to Collins, 23 September 1672.

50. Ibid, 259: letter of Gregory to Collins, 7 March 1672/3. The primary had received only a preliminary polish with "a cloath and puttie".

51. Ibid, 240.

52. Idem.

53. Idem. This has been noted, but without comment, by Desaguliers (1735), 212.

54. King (1955), 71.

55. This is assumed for example by Desaguliers (1735), 212; Pringle (1783), 210; Danjon & Couder (1935), 611; Turnbull (1939), 3; King (1939), 341; King (1955), 71.

56. Gunther (1930), 206: letter of Hooke to Boyle, 21 October 1664.

3.3 NEWTON'S FIRST TELESCOPE

Whereas Gregory had failed to put his telescope ideas into effective practice, Newton succeeded. The concept of his reflecting instrument had emerged incidentally in the course of his experimental work on the nature of light and colour. But far from allowing this to remain a theoretical design, Newton, with his extensive alchemical and metallurgical knowledge and his skill as an optical worker, forged ahead to construct the instruments themselves as demonstrable proof of his optical doctrine.

The first small reflecting telescope was made in 1668, but it remained almost unknown outside a small Cambridge circle until Newton constructed a second instrument three years later and this second telescope was brought to the attention of the Royal Society. There is no satisfactory account of Newton's prototype reflector, and apart from a few details relayed by John Collins to his correspondents, we have to rely on Newton's own comments and recollections. Enough information can however be gleaned to discount some recent suggestions about the instrument.

John Collins was first introduced to the work of the young Isaac Newton by Isaac Barrow, Lucasian professor of mathematics at Cambridge, in July 1669, when Barrow sent Collins some mathematical papers of a "friend of mine here, that hath a very excellent genius of those things".(1) When Collins had replied and expressed his satisfaction with the work, Barrow felt able to identify his friend: "his name is Mr Newton; a fellow of our College & very young".(2)

In this fruitful early period of Newton's work he had already made major advances in formulating his optical and dynamical doctrines, and had discovered the methods of fluxional calculus and approximation by infinite series that were to form the basis of his mathematics. The popular image however of Newton working in isolation at Woolsthorpe, and there evolving the conceptual framework of his theories all in one brief annus mirabilis, is now discredited.(3) Thus Whiteside has demonstrated Newton's dependence in this period on the resources of Cambridge University and Trinity College Libraries(4), and more recently Harrison has discussed the role played by Isaac Barrow's personal library, which was made freely available to Newton.(5)

Newton's rising star apparently induced Barrow to resign the Lucasion chair in favour of his 26 year old colleague in late 1669. Cohen suggests that Newton may have been referring to Barrow's active support when he wrote "Upon account of my progress in these matters he procured for me a fellowship ... in the year 1667 & the Mathematick Professorship two years later".(6) The friendship between the two men appears however to have been on a close professional rather than a personal level, and Whiteside has cautioned that Barrow was dissatisfied with the bar to the holding of other University appointments imposed by the conditions of the Lucasian chair, and may have been glad to relinquish it to a suitable candidate.(7)

Collins passed on the news of Newton's appointment to James Gregory at St. Andrews in November 1669:-

> "Mr Barrow hath resigned his Lecturers place to one Mr Newton of Cambridge, whome he mentioneth in his Optick Praeface as a very ingenious person, one who (before Mercators Logarithmotechnia was extant) invented the same method and applied it generally to all Curves ..." (8)

Barrow's scientific reputation rests on his Lucasian lectures on optics which were published by him in 1669 and initially were highly acclaimed. Newton had revised these for the press, and chose to continue Barrow's theme, putting forward however quite different ideas, in his own Lucasian lectures which began in January 1670. Of Newton's work in optics in the late 1660s very little is known - indeed Whiteside has described this as "one of the most intractable Newtonian dark eras"(9) - but during this period Newton organised and refined his early optical insights into the mature Lectiones opticae which he delivered as Lucasian professor. The lectures, deposited in the University Library as the statutes of the chair required, were the first public airing of Newton's new theories of the nature of light and colour, and at once rendered obsolete Barrow's earlier work; but their content was effectively unknown as Newton abandoned the publication of the Lectiones that he was preparing in 1672.(10)

Before he began his Lucasian lectures Newton was absent from Cambridge for about two weeks at the end of 1669. During this time he visited London, meeting Collins on two occasions, and following this a lively mathematical correspondence was established.(11) Collins was at the time corresponding with Gregory on similar topics, and by the end of 1670 he was acting as intermediary between Newton and Gregory. In a letter written in late 1670 Collins gave Gregory an account of those meetings a year earlier:

> "I never saw Mr Isaac Newton ... but twice viz somewhat late upon a Saturday night at his Inne ... And again I saw him the next day having invited him to Dinner: in that little discourse we had about Mathematics, I asked him what he would make the Subject of his first Lectures, he said Opticks proceeding where Mr Barrow left, and that himself was a practicall grinder of glasses, and had ground glasses for a pocket tube, but 6 Inches long, that magnified the Object 150 times whereby he did frequently observe the Satellites of Jupiter ... having no more accquaintance with him I did not thinke it becomming to urge him to communicate any thing ..." (12)

It seems certain that this 'pocket tube' was Newton's first reflecting telescope, the existence of which was not appreciated by the London scientific community for another two years: it was only when Newton's second instrument had been so favourably received by the Royal Society in 1671 that it became clear that this instrument had had precursors.

By his own account Newton concluded from his study of refraction that the degrading effect on image quality caused by chromatic aberration was inescapable, and by mid 1666 he had abandoned his attempts to grind non-spherical lenses.(13) He believed that there was no point in striving for geometrically ideal surfaces for object glasses when the heterogeneous nature of light that he had newly confirmed meant that refraction was necessarily accompanied by chromatic dispersion.(14) In his oft-quoted 1669 letter he expressed this belief as follows:-

> "I am Perswaded that were a Tube made after the Common way of the Purest Glasse, exquisitly Pollished with the best figure that any Geometrician (Des=Cartes &c) hath or can designe (which I believe is all that men hitherto attempted or wished for) yet such a Tube would scarce performe as much as an ordinary good Tube of the same length; And this however it may seeme a Paradoxicall assertion, yet it is the Necessary consequence of some Experiments which I have made concerning the Nature of Light " (15)

The Lucasian lectures themselves were introduced in a very similar manner a year later, with Newton stating immediately that a faulty understanding of the properties of light had led optical workers unwittingly to misdirect their labours. Their attempts to design and grind complex surfaces for telescopes became as pointless as "to plough the seashore" because of Newton's discovery that

> "a certain irregularity [in refraction] throws everything out, not only making conic figures little superior to spherical ones but determining spherical ones to be much less effective than they would be if this refraction were uniform." (16)

To justify this assertion he calculated the chromatic image size of a distant source and showed that for the long focus lenses then in use this was several orders of magnitude larger than the image size that would result from spherical aberration alone.(17) The example was used again in a lengthy letter sent to the Royal Society in February 1672 in which Newton set out his new doctrine of light and its experimental basis.(18) Since it was the different refrangibility of light that had frustrated attempts to perfect dioptric telescopes, Newton rather glibly noted that this realisation had "made me take Reflections into consideration", a gloss that was to involve him in dispute with Robert Hooke over the necessity of abandoning refractive schemes.

Although Newton may have turned naturally to reflecting optics when he recognised the inherent disadvantage of refractive elements, there are grounds for believing he was influenced to some extent by an acquaintance with James Gregory's Optica promota, published in London a few years earlier. In this work the parallel between refracting and reflecting imaging systems was explored in mathematical terms, and of course the optical scheme for a practical reflecting telescope, which has already been discussed, was proposed as a counterpart to the refracting telescope. Newton asserted in his early 1669 letter that he had been "perswaded of a certaine way wherby the Practicall part of Opticks might be promoted", which Turnbull has interpreted as an "obvious reference to the Optica Promota".(19) When, in May 1672, Newton was called on by Oldenburg to comment on the recently published description of Cassegrain's telescope, he made his debt to Gregory clearer:-

> "When I first applyed my selfe to try the effects of reflexions, Mr Gregory's Optica Promota (printed in ye yeare 1663) being faln into my hands, where there is an Instrument described (pag. 94) like that of Monsieur Cassegrain's, wth a hole in ye midst of ye object-Metall to transmit the light to an eye glasse placed behind it; I had thence an occasion of considering that sort of constructions, & found their disadvantages so great yt I saw it necessary before I attempted any thing in ye Practique to alter the design of them, & place ye eye glasse at the side of the Tube rather then at the middle." (20)

Newton appears in this to reserve to himself the initial step of considering reflecting elements, subsequently discovering Gregory's work, and only then considering the merits of specific optical schemes and rejecting the particular proposal made by Gregory as impractical. However, it should perhaps be noted that Oldenburg had asked him to review Cassegrain's proposals in the light of what Gregory had already published, and that if Newton was to make an effective claim for priority he would have to stress not only his familiarity with Gregory's work but also his appreciation of the need to adapt that design to make it practicable.(21) By this time Newton evidently had his own copy of Optica promota - Whiteside has noted that he had all Gregory's published works by late 1670(22) - but it is not known when he acquired this. He cannot have consulted the book in Cambridge University Library or Trinity College Library since neither had copies until some years later.(23) However it would seem most likely that Barrow's copy would have been acquired at an early date, and it would then have been available to Newton, whose access to Barrow's personal library may have dated from late 1667(24): this may well explain why he described the book as having "faln into my hands". In this case however, if we assume Hall to be correct in his dating of the earliest work on the telescope, it must be allowed that Newton's initial ideas were independent of Gregory's, although a knowledge at this time of Gregory's proposal may have been the impetus that led to the construction of Newton's first telescope.

Newton supposed that by using reflecting rather than refracting surfaces "Optick instruments might be brought to any degree of perfection imaginable"(25), but he foresaw considerable technical problems. The project would succeed only

> "provided a Reflecting substance could be found, which would polish a finely as Glass, and reflect as much light, as glass transmits, and the art of communicating to it a Parabolick figure be also attained. But these seemed very great difficulties, and I almost thought them insuperable, when I further considered, that every irregularity in a reflecting superficies [surface] makes the rays stray 5 or 6 times more out of their due course, than the like irregularities in a refracting one: So that a much greater curiosity would be here requisite, than in figuring glasses for Refaction." (26)

The continued presence of the plague in Cambridge obliged Newton to leave for his family home in Woolsthorpe in June 1666 (returning in April 1667) and it was "more than 2 years" (i.e. late 1668) before he continued this optical work.[27] It seems likely that his earliest attempts to produce achromatic images were experiments with compound lenses, which have been discussed by others, such as Bechler in 1975, and which were perhaps influenced by Hooke's published work. It is not yet clear how much of this was undertaken before the 1666-7 closure of the University, but Newton probably intended the late 1668 date to refer to the start of construction of the reflecting telescope.

Newton recounted that it was "amidst these thoughts" on the nature and shaping of a reflecting material that he left Cambridge[28], but Hall has suggested that the work had already taken an experimental turn. In an analysis of a student note-book kept by Newton between 1661 and 1665, he has proposed a revised chronology for the early optical experiments and has printed from the note-book a recipe for casting speculum metal that almost certainly relates to the telescope:

> "Metall for reflection may bee thus made. Melt throughly 3 pounds of Copper then take 4 ounces of white Arsenick 6 ounces of Tartar & 3 ounces of Saltpeter finely powdered together & put y^{m} into y^{e} melted copper & stir y^{m} well together with a rod of iron until they have done smoaking (but beware of y^{e} pernicious fume for ye Arsenick is poison). Then after a little blowing y^{e} fire to make it as hot as before, put in 6 ounces of Tinglass 2 ounces of Regulus of Antimony & after another blast or two put in a pound of tin

& stir it a very little & immediately cast it. The Tinglass makes y^e mettall tough & y^e Antimony makes it fine & of a steel colour too much of [it] will make it bleaw. The Saltpeter opens y^e pores of y^e mettal to let y^e filth evaporate & y^e Tartar helpeth to carry it away. [The following added in a different hand] If this mettall must be cast smooth line the sand mold with the smoak of a linke." (29)

By the time Newton resumed his telescope experiments in 1668 he had "thought on a tender way of polishing, proper for metall, whereby, as I imagined, the figure also would be corrected to the last", and he "began to try, what might be effected in this kind, and by degrees so far perfected an Instrument" that it could detect Jupiter's 4 major satellites.(30) Clear evidence for renewed optical activity is contained in Newton's account book for this period which lists the purchase in the summer of 1668 of a 'Lathe & Table', 'Iron worke for it', 'Drills, Gravers, a Hone & Hammer & a Mandrill'.(31) It is also apparent that Newton's practical interest in chemistry was developing and he was shortly to acquire two furnaces, one specifically for 'tin'.(32)

Very few constructional details of this first reflecting telescope are known. Newton in a letter of 1669 described it as being "but Six Inches in Length", noting that "it bears something more than Inch apperture"; the eyepiece was a plano-convex lens of 'depth' (i.e. focal length) 1/6 or 1/7 of an inch, giving a magnification of "about 40 times in Diameter".(33) The effective aperture of rather more than an inch has been taken as the clear aperture of the speculum by a number of commentators. Thus Brewster gives the speculum a diameter of 1", with that of the second telescope as 2.37"(34), whereas the Halls merely describe the second telescope as being "a little larger than the first".(35) In fact Newton restricted the useable aperture of the mirrors in two ways: firstly by masking off the edge zone in the mirror cell, and secondly by inserting a perforated disc at the eyepiece to act as a stop reducing the effective aperture further. In a later description Newton gave Oldenburg some typical dimensions, describing how

> "a Tube of six inches is capable of bearing an aperature (limited next the eye) so large that an obstacle of $1\frac{1}{4}$ or $1\frac{1}{3}$ of an inch in breadth shall be requisite to intercept all the light coming from one point of the object towards the concave metall ...
> And the whole breadth of the metall should not be lesse than two inches because its figure towards the edges will scarcely be so true as to be usefull." (36)

It therefore seems more plausible that the 1668 telescope 'bearing something more than an inch' aperture also had a speculum of around 2" diameter. Indeed this appears to be confirmed by a manuscript of this period in which Newton noted that

> "These [specula] that I cast for a tube of about seven inches were about a quarter of an inch thick and two inches wide. At first indeed I was moulding them thinner and less wide, but I could not make anything perfect from them." (37)

A manuscript scheme for a small reflecting telescope has been published by Turnbull, who has dated it as 1671/2, apparently on the basis of notes on the following sheet that refer to the use of a prismatic glass secondary mirror.(38) However in commenting on Newton's February 1672 account of his first telescope, Turnbull infers a link between that instrument and the one shown in the manuscript scheme.(39) Mills and Turvey have taken this a stage further by making the positive suggestion that these are one and the same instrument.(40) They have been influenced by the simplicity of the mount of the telescope in the manuscript, the unsatisfactory provision for focusing and the apparently longer focal length (over 8") of the mirror. The Newton telescope at present in the Royal Society has a primary mirror of this focal length, and the mirror's form and composition suggest to Mills and Turvey an early construction by Newton: these characteristics are therefore claimed to be "compatible with the speculum of his first telescope".(41)

In fact the telescope depicted incorporates a number of features described by Newton at a later date, and which can be ascribed with some confidence to the period after the construction of the second telescope. The manuscript, which will be described later, is more likely to have been a paper proposal than a representation of an actual instrument. One point is clear however: if the first instrument had a focal length of over 8", the magnification with an eyepiece of one-sixth or one-seventh of an inch would have been around 50-60 times rather than the 40 times that Newton stated in his 1669 letter.(42) Thus if we accept Newton's statement (and there are good reasons for believing this more readily than his later accounts) then we must discount the possibility of this surviving speculum being the mirror from the 1668 telescope. Indeed, the similarities between the specifications of the first and second instruments strongly suggest that the primary mirrors had near identical focal lengths of $6\frac{1}{3}$", and that in all probability they were ground on the same tool.(43) Newton's techniques for producing these mirrors will be dealt with in a subsequent section.

The quality of the mirrors appears to have been less good than might have been hoped for: the performance of the instrument might have exceeded that of a 6-foot long refractor, but "by reason of bad Materialls and for want of Good Pollish it represents not things so distinct as a 6. foote Tube will doe, yet I thinke it will discover as much as any 3. or 4. foote Tube especially if the Objects be Luminous." In spite of this he was able to see "Jupiter distinctly round and his Satellites, and Venus horned."(44) In 1672 he noted that with it he had been able to "discern Jupiters 4 concomitants, and [had] shewed them divers times to two others of my acquaintance": He "could also discern the Moon-like phases of Venus, but not very distinctly, nor without some niceness in disposing the Instrument."(45)

Newton at this time appeared to attach little importance to his telescope improvement, and he explained later to Henry Oldenburg, Secretary of the Royal Society, that if the Society had not shown interest he "might have let it still remained in private as it hath already done some yeares".(46) The instrument itself was no more than a prototype or model to indicate the potential of the reflecting principle:

> "though in it selfe contemptible [it] may be looked upon as an Epitome of what may be done according to this way, for I doubt not but in time a Six foote Tube may be made after this Method which will Performe as much as any 60. or 100. foot Tube made after the Common way;" (47)

News of the telescope reached only a handful of people. A Mr. Ent (usually identified as George Ent, FRS 1678) was one of these, as was an unknown friend of his to whom Newton wrote a brief description of the instrument in February 1669, of which a copy survives.(48) Another was John Collins, whose meeting with Newton at the end of 1669 has already been described. Collins in turn had informed John Flamsteed in January 1670(49), possibly in similar terms to those he used in a later letter to James Gregory. Newton was described to Gregory as a "practicall grinder of glasses" who "had ground glasses for a pocket tube, but 6 Inches long, that magnified the Object 150 times ..., and that such a glasse was naught for a short distance".(50) The term 'glasse' was used also in Flamsteed's reply of 24 January 1670, and was presumably being used in a loose manner by Collins to describe an imaging optical element.(51) Although a telescope optical system would necessarily employ two or more imaging elements, Turnbull cautions that the plural 'glasses' suggests a refracting instrument, and he supports this by quoting the performance of a 1" aperture refractor described in the manuscript Of Refractions.(52) It would seem more likely either that the familiar term was being used by Collins, who had not realised that this implied construction in a particular material, or alternatively that Collins had not appreciated that the primary element was in fact figured from metal, which in turn suggests that he had insufficient information to understand the new optical system. I favour the latter explanation for two reasons. Firstly, Collins does not appear to have spread the news of the invention to other Fellows of the Royal Society concerned in practical optics: this would have been a characteristic reaction had he appreciated the novelty of the device. Secondly, when in 1671 he heard Newton's second instrument described by Bernard in terms similar to those he himself had used about the first one, he failed to connect the two or to pass on a coherent description to his correspondent Vernon.(53)

In his reply to Collins' letter, Flamsteed wrote of his hope of improving the accuracy of astronomical positional measurement

> "especially if a short telescope may be made to perform as much as a long one, which you say that Mr Newton hath not only proved by demonstration, but fact. Sir, if it be no concealed secret, if you have liberty and may do it, I desire that you would please to inform me, of what glasses his small telescope is composed, how or in what figure ground, and how disposed in the tube. I intend to work some for my own use ... " (54)

Gregory's reaction to the letter from Collins was to express his admiration for "the pocket tube of Mr Newton, being onlie 6 inches long to magnifie 150 times". If this was a linear magnification then it was "incredible". If however it was expressed as an area magnification, giving a linear magnification of about 12 times, it might be adequate to detect the four main satellites of Jupiter "& consequentlie be extraordinarilie good": a volume magnification would certainly not be adequate.(55) An explanation for this puzzling magnification figure may perhaps lie in the fact that an area magnification of 1500 would give exactly the required linear figure of "about 40 times" (in fact 39 times). Collins was writing over a year after his discussion with Newton, and a possibly faulty understanding of the device would not enable him to relate this performance to that of a common refractor, and so he might have remembered the figure incorrectly.(56) Unfortunately Collins' reply of 25 March 1671, which might have clarified this point, is lost.

Gregory also expressed surprise at Collins' statement "that such a glasse was naught for a short distance": since he understood that the most desirable figure for an object glass for viewing nearby objects was closer to a sphere than to a hyperboloid (a much more difficult form to achieve) an object glass might be expected to perform well for closer objects. Newton's remark probably referred to the desirable paraboloid form for a mirror and contrasted it with the ellipsoid theoretically required if the telescope was to view nearby objects.(57)

Most of our information about this first reflecting telescope by Newton is contained in the two letters by Newton already cited. The more useful of these is the brief account dated 23 February 1668/9 of "my Successe in a small attempt I had then in hand" written to the unknown friend of Mr. Ent, and known from a transcription by John Collins that survives in the Macclesfield collection. It was first published by J.T. Desaguliers in 1735 in an account of the development of the reflecting telescope from 1663, based principally on extracts from the <u>Philosophical Transactions</u> and letters of Newton and James Gregory.(58) These letters were all from the papers of John Collins, then in the possession of William Jones, and subsequently bequeathed to the Earl of Macclesfield. This collection was used by the committee (of which Jones was a member) that was appointed by the Royal Society Council in 1711 to determine whether Newton or Leibnitz had priority in the invention of the calculus. It may have been the knowledge of the contents of these letters at this time that led to the suggestion of their publication after Hadley's 're-discovery' of the reflecting telescope in 1720. Collins sent a copy of Newton's letter to Gregory at St Andrews in late February 1672, adding some notes about the Society's recent telescope activities, but it is not known when the letter was first brought to his attention.(59) The most plausible suggestion is that the original recipient was prompted to do so by the enthusiastic reception given to the telescope by the Royal Society.

The second and fuller account is in the paper on dispersion which Newton sent to Oldenburg on 6 February 1672 and which was subsequently printed in the issue of the Philosophical Transactions distributed in early March.(60) Newton had promised in January to send in this "accompt of a Philosophicall discovery wch induced mee to the making of the said Telescope [this is the second instrument which was sent to the Royal Society] , & wch I doubt not but will prove much more gratefull then the communication of that instrument, being in my Judgment the oddest if not the most considerable detection wch hath hitherto beene made in the operations of Nature."(61) This letter remained the only account of the first telescope to be published in Newton's lifetime(62); and unfortunately it is also one in which the accuracy of the historical narration has been shown to be suspect.(63)

Notes and References

1. Turnbull (1959), 13: letter of Barrow to Collins, 20 July 1669.
2. Ibid, 14: letter of Barrow to Collins, 20 August 1669.
3. Westfall (1980).
4. Whiteside (1966), 37.
5. Harrison (1978), 6, accounts for the high proportion of alchemical books in Newton's library by noting that these were largely unrepresented in Barrow's library (as indeed in the University and Trinity libraries) and proposing that, until Barrow's death in 1677, Newton's book purchases were intended to supplement the books readily accessible in Barrow's library.
6. Cohen (1971), 306 n 14, citing an autobiographical note of c1716.
7. Whiteside (1970), 473; Whiteside (1969), xiv n14.
8. Turnbull (1959), 15: letter of Collins to Gregory, 25 November 1669.
9. Whiteside (1973), iv .
10. Bechler (1975), 103 n7. See also Turnbull (1939), 224: letter of Collins to Gregory, 14 March 1671/2.
11. Newton's entries in the Trinity College exit and redit book are published in Edleston (1850), lxxxv. The only suitable period of absence from Cambridge was 26 November to 8 December 1669, which suggests the first meeting took place on Saturday 27 November or 4 December. (Turnbull (1959) mistakenly proposes 30 November on p58, but gives the correct dates on p20).
12. Turnbull (1959), 53: letter of Collins to Gregory, 24 December 1670.
13. Newton claimed in his letter to Oldenburg of 6 February 1671/2 that he was 'applying' himself to the grinding of non-spherical surfaces in early 1666 when he began his dispersion experiments using prisms, and that this work had been 'left off' before the plague

forced him to leave Cambridge in June 1666: ibid, 92.

Both Hall (1955) and Lohne (1965) have argued that Newton has presented a simplified view of events and that this work was begun earlier. Hall had previously concluded from the manuscript record that Newton had written 1666 in error in his letter to Oldenburg and that the work had in fact been carried out in 1665: Hall (1948).

14. Bechler (1975) has demonstrated how Newton modified his public position on the necessity of dispersion in compound lenses (and therefore on the possibility of achromatic lenses) in response to criticism by Hooke, ultimately falsifying experimental detail in the Opticks to preserve the credibility of his doctrine. See the section on the reaction to Newton's second telescope.
15. Turnbull (1959), 3: letter of Newton to an unknown correspondent, 23 February 1668/9: see below p.76.
16. Whiteside (1969), 439: translation by Whiteside of the opening remarks of Newton's first Lucasian lecture on optics, delivered in mid January 1670, from the version retained by Newton (U.L.C. MS Add 4002) which predates the 1674 deposited text.
17. Ibid, 510 n60.
18. Turnbull (1959), 95: letter of Newton to Oldenburg, 6 February 1671/2, subsequently published by Oldenburg in Phil. Trans. R. Soc. Lond. 6 (1671/2), 3075-87.

    A similar result was repeated, but again the calculation not made explicit, in the Opticks (1704) I, 73.
19. Turnbull (1959), 6 n3.
20. Ibid, 153: letter of Newton to Oldenburg, 4 May 1672.

21. Newton by this time was aware that Gregory had been unsuccessful in his attempt to have a reflecting telescope made in London, and that Hooke in his subsequent trials with this telescope had fared little better.

22. Whiteside (1968), xii. The copy of Optica promota is now in the Turner Collection, University of Keele, and p93 is one of 8 pages marked by Newton's characteristic dog-earing: Gregory's telescope is described on p94. Harrison (1978), 154.

23. Personal communications from the Librarians of the University Library and Trinity College Library, Cambridge, 28 & 23 May 1980.

24. Barrow's library at the time of his death in 1677 is listed in Bodleian MS Rawlinson D878 'A catalogue of the Bookes of Dr Isaac Barrow Sent to S.S. by Mr Isaac Newton ... July 14. 1677'. Although Gregory's name is not amongst the authors cited by Barrow in the 1669 published version of his Lucasian optical lectures, Barrow was certainly familiar with his work. Thus Whiteside (1970) has demonstrated Barrow's dependence on Gregory's Geometriae pars universalis (Padua 1668) in the 1670 published version of the earlier geometrical lectures, and it seems most unlikely that the Optica promota would have been unfamiliar to Barrow in early 1668 when Collins was actively promoting Gregory's mathematical texts published in Italy. Another copy which may have been available to Newton at this time was that in the library of James Duport DD (1606 - 1679). Duport was Fellow and subsequently Vice Master of Trinity, and acted as tutor and friend to the young Isaac Barrow, resigning the Greek chair to him in 1660. He was created Dean of Peterborough in 1664, but returned to Cambridge in 1668 as Master of Magdalene College and was elected Vice Chancellor in

the following year.

25. Turnbull (1959), 95: letter of Newton to Oldenburg, 6 February 1671/2.

26. Ibid, 95.

27. Ibid, 95, 104 n15. Whiteside (1966), 40 n24.

28. Turnbull (1959), 95.

29. Hall (1948), 244.

30. Turnbull (1959), 96.

31. Whiteside (1968), xii.

32. Ibid, xiii.

33. Turnbull (1959), 3.

34. Brewster (1855) I, 66. The diameter quoted for the mirror of the second telescope appears to be that of the speculum now associated with (but not mounted in) the telescope preserved at the Royal Society of London which will be discussed in a subsequent section.

35. Hall & Hall (1971), xxiii.

36. Turnbull (1959), 128: letter of Newton to Oldenburg, 30 March 1672.

37. Ibid, 87: translation of U.L.C. MS Add 3973 containing instructions for casting speculum metal, from the chemistry section of the Portsmouth Collection. Turnbull has tentatively dated it to 1671/2. It is of course not clear whether the earlier unsatisfactory attempts included the mirrors of the 1668 telescope, nor how much smaller these specula were.

38. Turnbull (1959), 77 and plate II, reproducing U.L.C. MS Add 3969, f591. Notes from f592 are printed on p77, n4.

39. Ibid, 104 n17.

40. Mills & Turvey (1979), 135.

41. Ibid, 152. The suggestion is repeated by Bishop (1980).

42. Turnbull (1959), 3.

43. The second telescope had an eyelens of focal length "lesse then 1/6t part of inch" and a primary of focal length $6\frac{1}{3}$", giving a magnification of 38 times (i.e. 19/3 x 6). The eyelens of the first instrument had a focal length of "1/6 or 1/7th part of an Inch" and magnified "about 40 times", giving the primary a focal length of just over 6". The mirror diameter is of course quite independent of the focal length.

44. Turnbull (1959), 3. The recording of these observations helps to confirm that the telescope was indeed completed in late 1668, and yet surprisingly this aspect has not been investigated. Both Venus and Jupiter are standard objects of interest for small telescopes, but in order to discern detail such as the phase of Venus and the satellites of Jupiter the planets must be in positions in their orbits where they are well placed for observation from the Earth by being comparatively close and bright, and well separated from the Sun. This would be of particular importance for Newton's small instrument in which the reflectivity of the specula was low. (Mills and Turvey (1979), 147, have shown that using an alloy proposed by Newton the likely transmission efficiency of a telescope would be only about 20%). Jupiter must therefore have been observed within a month or so of opposition, and Venus within only a few weeks of greatest eastern or western elongation. Since Venus was described as 'horned' or in a cresent phase, it was therefore between elongation and inferior conjunction, which is also the time at which the planet is at its brightest: the period of observation is thus

further restricted to within a little over a month after eastern elongation or before western elongation. Jupiter and Venus were both at their most visible in October /November 1668 (the first time since July 1665 that this had occurred), and such an observational opportunity would certainly be expected on the reasonable assumption that the speculum metal dulled fairly rapidly and that the instrument was used only for a comparatively short period. Jupiter was in opposition on 17 November 1668, and Venus at greatest western elongation on 11 November 1668 appearing as the 'morning star' (deduced from Argoli (1677)). Because the ecliptic would be at its greatest inclination to the north in the hours before sunrise, Venus would rise over four hours before the Sun, and at its maximum brightness on 7 October it would be the most prominent object in the sky at about magnitude -4.2, high in the east. At the same time of night Jupiter would be visible high in the south-west, and with less than a month before opposition it would be at above magnitude -2.3 making it nearly as prominent an object as Venus. By contrast, Venus would not have been well seen near eastern elongation in June/July 1668 when it would have been low in the evening sky, setting only shortly after the Sun. Jupiter would not yet have reached quadrature and would have been poorly visible in the morning sky. Thus the likely time for Newton to have made the observations is October 1668, and we must certainly conclude the instrument was complete by mid-November 1668.

45. Turnbull (1959), 96.

46. Ibid, 79: letter of Newton to Oldenburg, 6 January 1671/2.

47. Ibid, 3. In fact, the several attempts by Newton, Hooke and Cock to produce large instruments in the 1670s were less than successful, and will be discussed in a subsequent section.

48. Ibid, 3: letter of Newton, dated 23 February 1668/9: see below p.76.

49. Flamsteed's reply to Collins' letter of 15 January 1669/70 (which is lost) is printed in Rigaud (1841) II, 92. Reference by Flamsteed to Robert Hooke's lens-grinding engine suggests that Collins may have been misled into thinking that Newton's telescope had a non-spherical objective lens. Grinding machines for non-spherical lenses by Hooke and Wren had very recently been discussed at the Royal Society.

50. Turnbull (1959), 53: letter of Collins to Gregory, 24 December 1670.

51. Rigaud (1841) II, 93: letter of Flamsteed to Collins, 24 January 1669/70.

52. Turnbull (1959), 59 n11.

53. See the discussion of Newton's second telescope that follows.

54. Rigaud (1841) II, 93: see above, ref. (51).

55. Turnbull (1959), 62; letter of Gregory to Collins, 15 February 1670/71.

56. Collins made it clear to Gregory that he would have liked to question Newton about the telescope, but felt inhibited from doing so: "having no more accquaintance with him I did not thinke it becomming to urge him to communicate any thing", but having heard from Barrow that Newton was obliged to deposit the text of his lectures in the University Library he knew that "coppies of them might be transcribed" there: Turnbull (1959), 54. Collins may however have discussed some aspects of Newton's optical experiments since on Flamsteed's letter, against the question

"how or in what figure ground", he has written: "To be done on the tool with fine sand": Rigaud (1841) II, 94.

57. Newton's comment would then be a general one on the geometry of reflectors rather than a specific reference to this particular instrument. It would appear to confirm the conclusion that Newton was indeed referring to the 1668 reflector and not to a refracting telescope (see above ref (52)).

58. Desaguliers (1735), letter 2, pp259-60.

59. The version sent to Gregory is printed in Turnbull (1939), 221-3. The copy of the letter from Newton is not in Collins' hand, and may be the original version obtained by Collins. The notes he has added describe events at Royal Society meetings on 18 and 25 January 1671/2, and in the covering letter dated 23 February 1671/2 (<u>ibid</u>, 219) he gives two transcriptions from the Journal Book to correct statements made from memory in his notes.
Below the copy of Newton's letter Collins noted that "The Tellescope therein mentioned hath been lately sent up to the Royall Societie", which suggests the notes were written before Newton's later letter was read on 8 February 1671/2. It is unlikely that the letter was known to him in December 1671 if we may judge from his correspondence with Vernon.

60. <u>Phil. Trans. R. Soc. Lond</u>. 6 (1671/2) 3075-87. Issue 80, dated 19 February 1671/2, containing Newton's letter, was distributed in early March. Huygens was sent a copy on 11 March, but due to an error on the part of Collins, Gregory was not sent his copy until early December.

61. Turnbull (1959), 82: letter of Newton to Oldenburg, 18 January 1671/2.

62. Excepting the ambiguous reference in the <u>Opticks</u>, for which see the section on Newton's third telescope.

63. Lohne (1965).

3.4 THE SECOND TELESCOPE, AND THE PUBLICATION OF NEWTON'S INVENTION

3.4a The Presentation to the Royal Society

From Newton's own account, there was a break in his telescope making activities after the first instrument had been completed in 1668. "From that time I was interrupted till this last Autumn [1671], when I made the other" which was "sensibly better than the first (especially for Day Objects)".[1]

News of Newton's activities had reached London by early December 1671, possibly relayed initially by Thomas Gale (?1635-1702), regius professor of Greek at Cambridge from 1666 to 1672, and like Newton a Fellow of Trinity College. Gale may have had an interest in promoting scientific matters since the Trinity copy of Hooke's Micrographia is inscribed as having been presented by him.[2] One might indeed speculate that he was one of the "two others of my acquaintance" who made observations with the first instrument.[3]

Gale wrote to Edward Bernard (1638/9-1696) at Oxford, Christopher Wren's deputy as Savilian professor of astronomy, informing him of the telescope, and Bernard passed the news on to John Collins. Bernard had been answering a mathematical enquiry which Collins had received from Francis Vernon in Paris, and the draft of Collins' reply to Vernon, dated 14 December 1671, survives:

> "Your communication I imparted to Mr Bernard, and when I had wrote hitherto I received his answer, which I shall give you ...
>
> He saith, that Mr Gale of Cambridge writes him word that Mr Newton (Barrow's successor) hath abbreviated a sixteen feet tube to the length of a span, which is a most happy invention.
>
> I further add, that the eyeglass is placed towards the object, the object glass from it; the eye looks in through the middle of the side, and sees all by reflection, as 'tis said, in the same perfection as, and certainly takes in much more than, when the glasses are placed in their long tube.

> Sir Samuel Morland's [loud speaking] Trumpet is now publish[ed]: oh that you had one of them, wherewith to display its own fame and the due praise of this telescope!" (4)

It is not known whether the Council of the Royal Society heard of the telescope from Collins, direct from Bernard, or from another source. Collins certainly expected that Bernard had informed others, for he wrote later that month to Vernon: "I suppose Mr Bernard writt the same to you as he did to me, upon the Authority of one Mr Gale of Cambridg (whom I know not)".(5) Amongst those who must have known of the instrument at this stage were Barrow, who remained in regular correspondence with Collins, and the mathematician Seth Ward (1617-1689), Wren's predecessor as Savilian professor of astronomy and now Bishop of Salisbury. Ward had pressed his ecclesiastical patronage on Barrow after the latter's resignation from the Lucasian chair: the two men were on the closest terms and Barrow often stayed at Salisbury.(6) Ward was also at the time a member of the Royal Society's Council, and his role in urging the Council to take an interest in Newton's invention may be inferred from the fact that it was he who proposed Newton for membership.(7) In any case, it seems that a request was made around the middle of December for the instrument to be examined in London, and Newton noted soon afterwards that "the communication" of the telescope had "been desired".(8)

The Halls suggest that interest at the Royal Society in Newton's telescope may have been stimulated by the receipt of a letter from Gottfried Wilhelm Leibnitz in early November 1671.(9) In this Leibnitz mentioned the use of "universal" lenses (that is, lenses which will bear any aperture without having to be stopped down(10)) and "reflecto-refracting telescopes such as came into my head": no one as far as Leibnitz was aware had considered using these.

Bearing in mind the interest in optical affairs that followed the publication of Barrow's Lectiones Opticae, it is likely that the content of his letter would have been circulated, although surprisingly there is no record of its having been read at a Society meeting. The Halls conclude that if it had been seen by anyone who knew of Newton's telescope then attention would have been drawn to the instrument's existence. They also note a change in Oldenburg's attitude to Newton's work: now that he realised that Newton's efforts were not restricted to purely theoretical matters, but that he appeared to have made an important discovery in practical optics, Oldenburg was anxious to open a correspondence with Newton and to spread news of the discovery in order to protect Newton's rights to the invention. This typically Baconian response to the useful application of science may however have been influenced by the fact that the Society was already actively encouraging work to improve telescope optics and at the end of the previous session had been inspecting Francis Smethwick's latest telescope.(11)

By the end of January 1672 John Flamsteed, writing from Derby, had "reacceaved severall informations from Cambridge yt Mr Newtons tube is now delivered into ye hands of Dr Barrow to be by him presented & publisht before ye Society"; in addition, a relation of his who had recently come from Cambridge was able to give him a rather confused (and possibly second-hand) description of "this prodigie of arte".(12) Although Barrow is not mentioned elsewhere in this context, and although he was certainly not otherwise active in the Society's affairs, it is probable that he did act as courier. Indeed he would have been an obvious and well qualified emissary who could persuade his successor Newton to allow him to return with the instrument to London. Barrow at this period apparently divided his time between Salisbury and Whitehall, where from 1670 he had been one of Charles II's Chaplains-in-Ordinary.(13) Moreover he had retained his links with Trinity College, for he had resigned only his Lucasian chair and not his fellowship, and he was in fact to return as Charles' personal choice for the vacant mastership in 1672. Barrow was apparently in Cambridge at about the right time, since in December 1671 he became one of the 16 College Preachers at Trinity, and this may have been the occasion when the telescope was collected.(14)

The circumstances of the telescope's arrival in London are not known. Collins had clearly not seen it when he wrote to Vernon on 14 December, from which it is probably safe to assume that it had not yet arrived in London.(15) The telescope was not mentioned at the Society's meeting on 21 December, the last before the Christmas recess. However at that meeting Newton was proposed as a Fellow by Ward, perhaps indicating that the telescope had already been received and its significance appreciated. Collins had examined it himself by the time he wrote to Vernon on 26 December:

> "As to Mr Newton's Tellescope ... it hath been brought up for his Ma[jes]ties perussal and I have seen an object in it."

After giving a brief description, Collins noted that it gave an image

> "clere without colours, and as much magnified as it could be by an ordinary Tellescope of 5 or 6 foot long ... it is somewhat difficult to place upon an Object, and some object that it is not so lightsome as [i.e. the image is less bright than in] the Ordinary Tubes of the length aforesaid." (16)

The accounts drawn up over the next few days by Oldenburg of a trial of the telescope which he described as being "the first attempt to see and examine it here"(17) are essentially the same as that of Collins, and it appears clear that they describe the same event. The test was conducted at Whitehall Palace(18) and was obviously considered an occasion of some importance. Apart from Collins, and presumably Oldenburg, those present were Lord Brouncker and Sir Robert Moray, respectively President and Vice President of the Society, together with Sir Paul Neile, Christopher Wren and Robert Hooke, who were all experienced in figuring telescope lenses.

A careful comparison was made between the reflector and a small 25 inch Galilean refractor. The apparent size of a distant test object was found by viewing it through each telescope in turn with one eye and drawing an image coincident with this on a piece of paper held at a fixed distance from the other eye. The reflector was found to give an image 2½ times larger than the refractor (although Oldenburg initially gave this as 3 times) indicating that the reflector could be considered as equivalent to a common refractor of over 5 foot. This conclusion was not reached without some disagreement, which one may judge to have been warm from Oldenburg's account of it to Newton:

> "Though divers of ye most skillful examiners agreed yt your Tube magnified [this much more than the other telescope], yet there were others, well versed in Optic glasses, yt, though they could not disprove that mensuration, yet were positive to affirme, yt yt excesse magnitude did not appear such to their eye." (19)

Oldenburg's admission that "after repeated experiments the Masters Brouncker, Wren and Hooke agreed" allows us to deduce that the objector was Hooke, providing a foretaste of the experimental scepticism that Newton was later to find so disagreeable.[20]

The object viewed in this test was "an iron crown placed as an ornament on a weathervane at the distance of about three hundred feet".[21] Attempts to identify this from contemporary views, and therefore to help establish the place from which the test was conducted, have been inconclusive. However, the most likely candidate was the weathervane erected over the King's Withdrawing-room (the 'Vane Room') at the junction of the Privy Gallery with the line of the Stone Gallery. This was at the north-east corner of the Privy Garden opposite to Sir Robert Moray's apartments and at about 300 feet from them. Although no illustration of this can be found, it is known to have been the principal weathercock in the palace and to have been an ornamental structure bearing the King's Arms.(22)

Apart from the predictable difficulties experienced in manipulating the telescope and locating objects, the reaction of this committee of the "most eminent in Opticall Science and practice" was to applaud the instrument and to insist on the Society securing recognition abroad of Newton's priority to the invention. This was to be done, Oldenburg informed Newton, by sending a formal description, of which he now enclosed a draft, in

> "a Solemne letter to Paris to M. Hugens, thereby to prevent the arrogation of ... strangers, ... it being too frequent, ye new Inventions and contrivances are snatched away from their true Authors by pretending bystanders". (23)

So urgent was this thought to be that Oldenburg had already penned a hasty note to Christiaan Huygens the previous day, although he had not informed Newton.(24) The draft description and illustration were returned by Newton with suggested alterations a few days later, and these were then incorporated by Oldenburg into the version sent on to Huygens.(25)

Huygens was at the time the most conspicuous figure in Continental science, widely celebrated in mathematics and astronomy, and recognised as the leading expert in practical optics. He had settled in Paris with a Royal pension in 1666, the most significant figure to do so as a result of the efforts of Jean Colbert to attract influential scientists to Paris to promote French science and in anticipation of the founding of the Académie des Sciences. His wide correspondence and his links with the Académie made him an ideal intermediary in establishing Newton's priority firmly. The fact that he was already in close touch with the Royal Society through his long standing correspondence with Sir Robert Moray would no doubt reassure Moray's colleagues that he would be an effective ambassador for the Society's claims on Newton's behalf.(26)

Moray's influence may also be detected in the proposal that the telescope be demonstrated to the King. Charles II had extended his patronage to the embryo Society in 1660, influenced as much by his respect for the royalists amongst its founder members, notably Moray, Neile and Brouncker, as by any clear wish to foster experimental philosophy. Moray's ready access to Charles, both as a trusted personal friend and as an influential political adviser, was of great value to the Society in its early days; and it was for example Moray who played the prominent part in securing the Society's various Charters. Charles' interest in science if not profound was certainly practical, and he maintained a personal laboratory at Whitehall Palace.(27) For some time Sir Robert Moray was in charge of it, and no doubt discussions there provided an excellent opportunity for him to keep Charles in touch with the Royal Society's work. Although the King apparently never attended a meeting of the Society, his scientific comments and enquiries, and occasional news of royal experiments, were relayed to the Society largely by Moray. Thus for example, at the meeting before Newton was proposed as a candidate for fellowship, Moray read some observations recently made by Charles of an unusual formation of frost.(28)

The move to demonstrate the telescope before the King may perhaps be seen as a reaction to the perceived scientific importance of the device, or even as a courtesy designed to revive their Patron's waning interest in the Society. A more attractive proposition is that a parallel was drawn with Samuel Morland's loud-speaking trumpet, or 'tuba stentorophonica', which had been associated with the Society and had been the subject of much discussion for a number of months. Charles, with his passionate interest in promoting his naval service, had been sufficiently impressed with the military potential of this invention to encourage further development and to arrange for shore-to-ship trials which led to a number being commissioned for use on naval warships.(29) Perhaps the new telescope, with its compact form and comparatively high magnification, would be seen to have a similarly important role and attract official stimulus for its development?

Unfortunately Charles's reaction to the instrument is not known so we can only assume that he was not strongly enthusiastic. A search of the State Papers Domestic, and the Lord Chamberlain's Papers has failed to produce an account of the 'Royal View'.(30) The occasion was referred to only briefly at the 11 January 1672 meeting when the Society reassembled after the recess, and when Newton was actually elected a Fellow:

> "Mention was made of Mr Newton's improvement of telescopes by contracting them; and that that, which himself had sent hither of that kind to be examined, had been seen by the King, and considered also by the president, Sir Robert Moray, Sir Paule Neile, Dr Christopher Wren, and Mr Hooke at Whitehall, ..." (31)

Oldenburg did not mention a presentation before the King in his letter to Newton of 2 January in which he gave the initial scientific reaction, and so it may be that this had not yet occurred. A royal inspection only shortly before the 11 January meeting might mean that it had been decided to delay this viewing until approval had been given by Newton of the draft description: this was received on 8 January. It might also help account for the absence of the instrument from the 11 January meeting: its first (and indeed only) recorded appearance was at the 18 January meeting, when "Mr Newton's new Telescope was examined and applauded".(32) This might have been confirmed by the letter which Oldenburg wrote to Newton shortly after the 11 January meeting but which is not known to survive.(33) Oldenburg had been instructed to write

> "to signifie to him his Election, and also to thank him for the Communication of this Telescope, and to assure him that the Society would take care, that all Right should be done him in the matter of this invention." (34)

He went further however, and it is clear from Newton's reply that he discussed Hooke's attempts to find a suitable speculum alloy(35); and it is perhaps not unreasonable to suppose that such a prestigious event as the telescope's demonstration to the King would have been mentioned also.

In the absence of this letter it is not possible to establish whether ownership of the telescope passed to the Society. Indeed the question of its ownership does not seem to have been raised, unless the following extract from Newton's first letter to Oldenburg was taken to mean that the instrument was being donated:

> "... I was surprised to see so much care taken about securing an invention to mee, of wch I have hitherto had so little value. And therefore since the R. Society is pleased to think it worth the patronizing, I must acknowledg it deserves much more of them for that, then of mee, who, had not the communication of it been desired, might have let it still remained in private as it hath already done some yeares."(36)

In subsequent letters it is merely referred to as having been "sent" to the Royal Society. It is however prominently described in Nehemiah

Grew's Musaeum Regalis Societatis (1681) which has as its subtitle 'a Catalogue & Description of the Natural and Artificial Rarities Belonging to the Royal Society and preserved at Gresham Colledge'.(37)

The Society's Museum or Repository would have been the normal home for a piece of donated apparatus. However this may not initially have been so for the Newton telescope since unusually it was not directed to the Repository in the minutes of meetings, nor indeed was it at any time associated in the minutes with the Repository or individually with Robert Hooke, the Society's Curator. The Council members concerned were anxious to restrict information about the invention, in the first few weeks at least, and this argues for it having been kept in more guarded circumstances. The links with Moray and Whitehall suggest the instrument was kept by him, and it may easily have remained with him until the Society gave up their temporary rooms in Arundel House and returned to Gresham College in 1674. Much of the Society's accommodation had been requisitioned by the City after the Great Fire. Hooke's lodgings, provided with his Gresham chair, were secure; and the Society's collections remained there under his care, but now relocated and effectively in store.(38)

Notes and References

1. Turnbull (1959), 96: letter of Newton to Oldenburg, 6 February 1671/2.

2. The copy is inscribed as having been presented in 1664. Publication was probably in January 1664/5: Pepys bought his copy on 20 January (Gunther (1938), v) and Gale's purchase is likely therefore to have been made within two months of publication. Micrographia was an important stimulus in Newton's early optical work (Whiteside (1967), 549) and the extensive early notes by Newton reprinted by Keynes (1960) may have been made from the Trinity copy. Gale resigned his chair in 1672 to become high master of St. Paul's School, London, where the young Edmond Halley was one of his pupils. He was elected FRS in 1677, but does not appear to have taken an active part in the Society's scientific work. He served as a Secretary of the Society for eleven years, rarely however attending Council meetings. A number of items in the Society's repository were presented by him.

3. A.J. Turner goes as far as to state that he was: Turner (1977), 74.

4. Rigaud (1841) I, 176: draft letter of Collins to Vernon, 14 December 1671. The comparison with a 16-foot refractor is clearly an exaggerated claim. It is just possible that this may have been introduced to demonstrate the instrument's dramatic superiority over Francis Smethwick's 6-inch telescope, which had been shown to the Society in June and which had been compared with a 14-inch refractor (Birch (1756-7) II, 484). Oldenburg, writing to Huygens on 1 January 1671/2 with the initial announcement of Newton's telescope, certainly couples accounts of the two

instruments together, and equates the performance of Smethwick's telescope to that of an ordinary 18-inch refractor (Hall & Hall (1971), 445). Samuel Morland's <u>Tuba Stentoro-Phonica</u> was published in late 1671.

5. Roy. Soc. MS LXXXI 'Commercium Epistolicum', item 13: draft letter of Collins to Vernon, 26 December 1671.

6. Osmond (1944), 199.

7. At the meeting of the Society held on 21 December 1671 "Mr. ISAAC NEWTON, professor of mathematics in the University of Cambridge, was proposed candidate by the lord bishop of SALISBURY": Birch (1756-7) II, 501. Ward was also one of the three assessors to whom Newton's February 1672 paper on the theory of colours was sent for comment.

8. Turnbull (1959), 79: letter of Newton to Oldenburg, 6 January 1671/2.

9. Hall & Hall (1971), xxiv. A translation of the letter is given in <u>ibid</u>, 296: letter of Leibnitz to Oldenburg, 15 October 1671 [O.S.].

10. <u>Ibid</u>, 299 n3.

11. Birch (1756-7) II, 484: meeting of 22 June 1671.

12. Turnbull (1959), 88: letter of Flamsteed to Collins, 31 January 1671/2. Turnbull suggests the information came from Flamsteed's cousin, Wilson. Flamsteed's "severall informations from Cambridge" (a phrase repeated in his letter to Oldenburg of 5 February 1671/2) may refer to a correspondence on optical matters which he was conducting at the time with Richard Wroe (1641-1718), another Fellow of Jesus College, who was however resident in Cambridge: the correspondence is mentioned in

Flamsteed's letter to Collins of 17 April 1672, Turnbull (1959), 146. I am indebted to Prof. E.G. Forbes for this suggestion.

13. Osmond (1944), 154.

14. Ibid, 198. The Librarian of Trinity College, Cambridge, has been unable to determine whether there was any ceremonial connected with the appointment which would have required Barrow's presence (personal communication, 2 July 1980).

15. Rigaud (1841) I, 176. Collins appears to have played a part in pressing for the telescope to be examined by the Society, and certainly he was given a privileged opportunity to view it. The customary informal meeting following the Society's meeting of 14 December may have given Collins the opportunity to raise the matter. Indeed it is quite possible that the decision to seek an inspection of the telescope in London could have been taken as late as this.

16. See above, ref (5).

17. Hall & Hall (1971), 446: translation of letter of Oldenburg to Huygens, 1 January 1671/2.

18. The only reference to its being at Whitehall is in the Royal Society MS Journal Book, meeting of 11 January 1671/2: the telescope "had been seen by the King, and considered also by the president, Sir Robert Moray, Sir Paul Neile, Dr Christopher Wren, and Mr Hook at Whitehall". As will be shown, the viewing by Charles II was on a separate occasion; but both apparently took place at Whitehall Palace.

19. Turnbull (1959), 73: letter of Oldenburg to Newton, 2 January 1671/2.

20. Ibid, 76: translation of the draft description by Oldenburg of Newton's telescope prepared for transmission to Huygens. This reference was omitted from the final version sent to Huygens on 15 January 1671/2.
21. Hall & Hall (1971), 473: translation of the description of Newton's telescope enclosed with Oldenburg's letter to Huygens of 15 January 1671/2.
22. Dugdale (1950), 49.
23. Turnbull (1959), 73: letter of Oldenburg to Newton, 2 January 1671/2.
24. Hall & Hall (1971), 445: translation of letter of Oldenburg to Huygens, 1 January 1671/2. It appears that Oldenburg had delayed writing in the hope of sending issue 78 of Phil. Trans. which was however still not printed at the time of writing.
25. Turnbull (1959), 79: letter of Newton to Oldenburg, 6 January 1671/2. Unfortunately not all the suggestions were followed: see below.
26. The same could not have been said two years later, when a priority dispute flared between the Society and Huygens over the isochronism of the cycloid: Hall & Hall (1975), xx.
27. Dugdale (1950), 78, 79; Hartley (1960), 42, 246.
28. Birch (1756-7) II, 500.
29. Dickinson (1970), 40-4.
30. Personal communication from G. Wickham, Public Record Office, May 1975; and F.H.B. Daniell (ed) Calendar of State Papers, Domestic Series, December 1671 to May 17th 1672 (London 1892).
31. Roy. Soc. MS Journal Book, meeting of 11 January 1671/2.
32. Ibid, meeting of 18 January 1671/2. Since the 'official' description of the telescope was read at the meeting there can have been no case for withholding the instrument to protect it from infringement.

33. This was written in the period 11-17 January 1671/2, and not merely after the 6th as Turnbull (1959), 82, allows, since Newton refers specifically to his election as a Fellow.

34. Roy. Soc. MS Journal Book, meeting of 11 January 1671/2.

35. This work is normally ascribed directly to Christopher Cock, the optical worker commissioned by Hooke, because Birch uncharacteristically failed to extract the reference from the minutes of the 11 January meeting. See below.

36. Turnbull (1959), 79: letter of Newton to Oldenburg, 6 January 1671/2.

37. Grew (1681), 360.

38. See below, p.190 ref. (14).

3.4b Description of the Second Instrument

Much more is known of the second telescope than of the first, of which we know only the barest details although we have the assurance that it was "in the essential parts of it like that I sent to London".(1) There are two principal accounts, the earlier being the description by John Collins sent to Francis Vernon in Paris on 26 December 1671 after Collins had tried the telescope:

> "The Subs[tance] is a Cylinder of about 7 inches long and $2\frac{1}{4}$ I[nches] Diam open at one End, at the other is a Spherical Concave Speculum of Metall [here 'lyable to rust or tarnish' is deleted] obnoxious to ye inconven[ien]ce of rust or Tarnish.
>
> Out of the side of the Cylinder a Wyre so holds a Cutt of plane looking glasse inclined and as bigg as a penny, that it may be in the focus of the former, the eye lookes in at a hole in the side of the Cylinder as big as a great Pins head through a glasse, and sees the object clere without Colours ...
>
> A screw at ye end remooves the Mettaline Speculum a little too and agane to serve in stead of Drawing. The tube is fastened with a foote to a mooveable Ball of Wood which rests in a Spherick Disc that hath a flatt Base ..." (2)

The second is the description, and accompanying illustration which Oldenburg was instructed to draw up and send to Huygens. This ran as follows in Turnbull's translation of the original Latin:

> "AB is a concave metallic speculum attached to the bottom of the tube of radius 14 English inches.
>
> CD is a plane oval metallic speculum fastened to an iron rod and fixed to a brass ring movable within the cavity of the tube.
>
> F is a glass lens with a plane upper face and convex lower face and of about $\frac{1}{2}$ inch radius.
>
> GGGG the fore part of the tube, firmly clasped by a brass ring HI, so that it cannot easily be moved.
>
> PQKL the back part of the tube, securely fixed to a brass ring PQ.

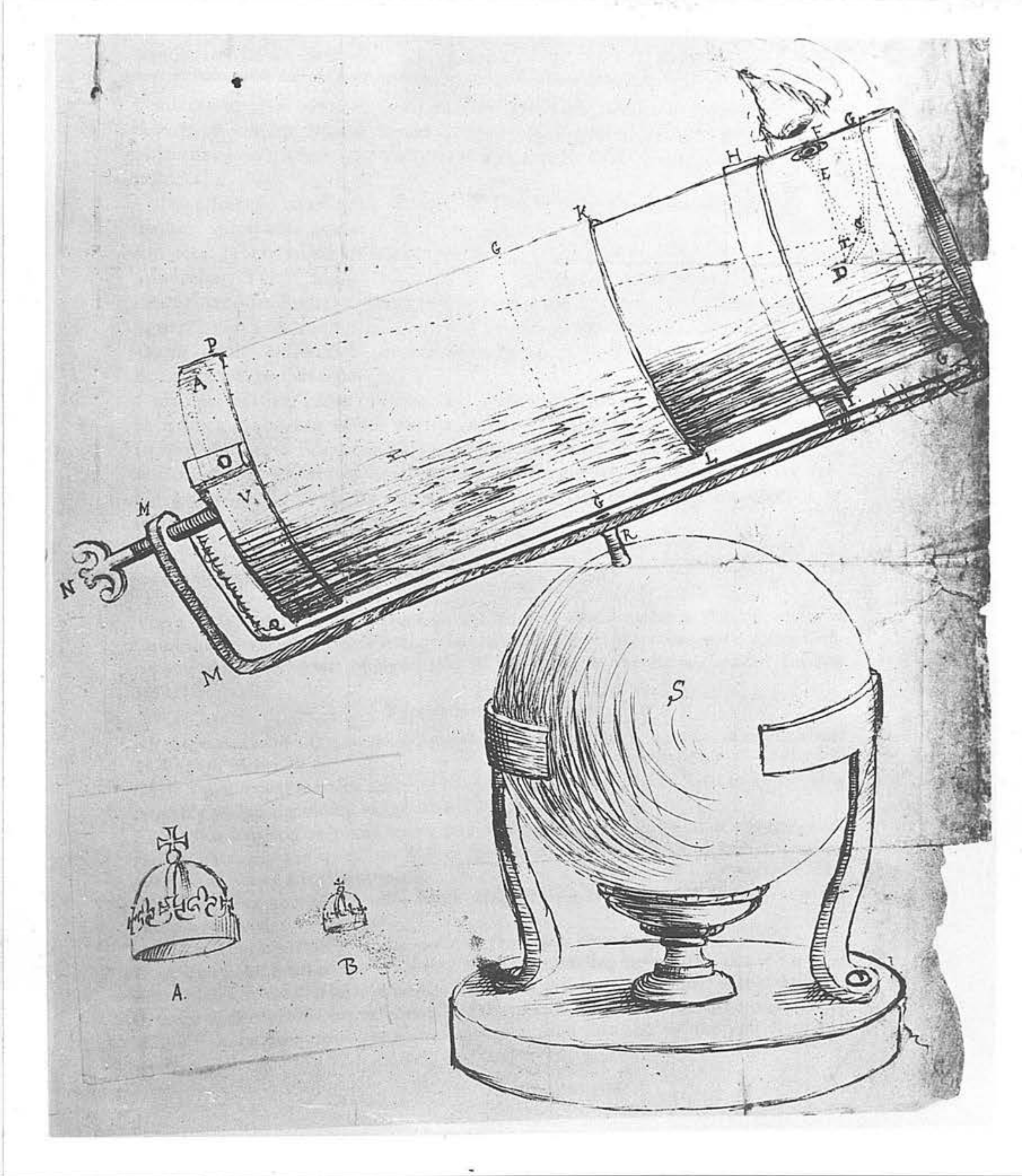

Fig.2. Isaac Newton's second reflecting telescope as drawn for the Royal Society in 1672 to accompany Henry Oldenburg's formal description of the instrument. Manuscript at the Royal Society; reproduced from Turnbull (1959).

O an iron hook fixed to the brass ring PQ, and extending beyond the axis of the tube into which a screw N is let and pushes forward or withdraws the hinder part of the tube, in order to discover the correct distance of the specula, while the front part remains fixed.

NMGI [i.e. MMRI] a crooked iron sustaining the tube, and fastened by the nail R to the wooden globe S.

The centre of the plane speculum CD is placed on this axis of the tube so that the perpendicular dropped upon it from the centre of the lens makes a right angle with the axis: and the image of the object cast upon it by the concave speculum is reflected towards the focus E of the lens." (3)

The description was sent off to Newton for correction, Oldenburg writing to say that

"it was not thought fit to send this away without first giving you notice of it, and sending to you ye very figure and description, as it was here drawne up; yt so you might adde, & alter, as you shall see cause; wch being done here wth, I shall desire your favour of returning it to me wth all convenient speed, together wth such alterations, as your shall think fit to make therein." (4)

The draft description and illustration were duly returned by Newton four days later.(5) They are still in the Royal Society archives where they remain the best source of information about the instrument, and have been appealed to on at least one occasion in the chequered history of the Society's Newton telescopes. The corrections which were recorded on the draft by Oldenburg were restricted to the focal lengths of the elements. The radius of curvature of the primary was "more justly $12\frac{2}{3}$ or 13 inches" (which Oldenburg noted as nearly 13 inches), and the radius of curvature of the eyelens was one twelfth of an inch "if not lesse". Newton had obtained these figures by the previous use of direct imaging of the Sun, obtaining focal lengths of $6\frac{1}{3}$" and 1/6", and he was now able to confirm these by measurement of the grinding tools used in their construction:

"By the tooles also to wch they were ground I know their dimension, & particularly measuring the diameter of the hemispherical concave in wch ye eye glasse was ground I find it the 6t part of an inch." (6)

The ratio of the two focal lengths is the same as the ratio of the image sizes produced by the two optical components of a distant object of given angular size, and thus gives the mangification of the instrument. Oldenburg inserted Newton's statement to this effect, which gave the magnification as 38 times. Newton was able to make a rough check on this figure because Oldenburg in his description had given some details of the refracting telescope used in the comparison test at Whitehall. This had been a "common tube" (or Galilian refractor) of 25" long, with a double concave eyelens of 2" radius of curvature,(7) giving the focal lengths of the two components as about 27" and 2". This would give the magnification of "13 or 14 times" noted by Newton, and having measured the ratio of apparent sizes of the test object as seen through the two telescopes as $2\frac{1}{2}$ times, he could deduce that his instrument had magnified by about 34 times. However, he commented only that from Oldenburg's figures this method gave a magnification "almost as much" as he had assigned to the instrument.(8) On a later occasion, when it suited his purpose better to claim a lower magnification, he appealed to an alternative method of measurement, which must surely be this one, and which gave a figure of "about 35 times".(9)

The drawing of the telescope shows an instrument with a body tube in two parts sliding within one another to allow it to be focused. It is mounted on a limb which is fixed on the ball of a large ball-and-socket joint, allowing the desired orientation of the telescope to be set. The tube was "firmly clasped" at its open end by a brass band attached to the limb. At the other end, where the speculum was housed, the tube was "fixed immovably" (in the Halls' translation (10)) to another brass band connected to the limb by a focusing screw. The primary speculum itself is indicated only by a dotted line tracing its circumference and suggesting a diameter close to that of the smaller of the body tubes, which Collins indicated to be $2\frac{1}{4}$" diameter. Unfortunately Newton's suggestion to Oldenburg that the physical diameter of the primary be given in the formal description of the instrument was not followed up.(11)

The brass band surrounding the lower part of the tube obscures any detail that might otherwise have been visible of the mounting for the mirror. It was possible to remove the mirror, since on one occasion Oldenburg was told that the speculum should "bee taken out and rubbed wth gentle leather" if it became dull(12), and yet the inference from Newton's later discussion of ways to protect the mirrors from tarnishing is that it could only be removed by dismantling the telescope.(13) The obvious structure to hold the mirror would seem to be a turned wooden mirror cell of the type fitted to the telescope at present in the Royal Society. In this the mirror is positioned with the outer edge of its front surface against a flange in a wooden ring, and held in place from behind by a threaded cap which screws into the ring, which in turn is glued to the end of the pasteboard tube. However, the presence of the focusing screw behind the mirror cell would prevent the end cap from being removed; this could only be done if the tube could be withdrawn from the brass band, but this is specifically stated to be "fixed immovably". Had such a cell been used it would surely have been fitted to the outside diameter of the tube, as Newton proposed in a later telescope design to be discussed in a subsequent section.

Instead, the drawing shows the external diameter to be the same as that of the tube, which would require the machined parts to fit in the very narrow gap between the mirror and the tube - a very much more difficult solution, and one perhaps not realisable at that time.
A more plausible proposal is that a wooden end cap, probably with a hollow on the inside face, was glued into the end of the wider tube, and the mirror dropped down the tube to rest in the hollow. A short length of the narrower pasteboard tube, perhaps with a small flange attached to one end, was then simply pushed down the wider tube to locate the front surface of the mirror and hold the mirror in place.
A rather similar solution was adopted for locating the secondary mirror which is mounted on a sprung brass ring sliding within the narrower tube.
Although this is hardly a sophisticated method of mounting the primary, it has the advantage of being mechanically simple, and is perhaps more in keeping with the instrument's 'prototype' status. It would also help account for the collimation difficulties Newton experienced:

> "With the Telescope wch I made I have sometimes seen remote objects ... very distinct ... And at other times when it hath been otherwise put together it hath exhibited things not without some confusion. Wch difference I attributed chiefly to some imperfection that might possibly be either in the figures of ye mettals or eye glasse ..." (14)

The method of removing the primary would then be to withdraw the inner tube from the upper brass band, which is not "fixed immovably" but merely "firmly clasped ... so that it cannot easily be moved": significantly the band has been positioned so that it does not have to pass over the eyepiece. The inner retaining tube would then merely be withdrawn as well. This interpretation of the mirror mounting would appear to be consistent with the description of the instrument's operation and with the features shown on the drawing.

The secondary mirror is indicated by a dotted outline showing a small thin flat reflecting surface inclined at 45° to the axis of the tube, reflecting the image towards the eyepiece. It is shown supported on a pillar mounted on a short cylindrical ring within the body tube. The eyepiece is shown within a larger circular feature and apparently recessed within the tube. This turns out to be a lead cell carrying the eyepiece stop:

> "The plane side of the eye glasse is apt to bee soiled wth dust falling upon it. And therefore the little leaden ring put into ye orifice of the bigger leaden barrell to moderate its aperture must bee sometimes taken out, & the glass wiped wth leather done upon the small end of a stick, ... but care must bee taken that the said ring bee not lost, for wthout it objects appeare very confused at the edges of ye apparent space." (15)

Although the original illustration of the telescope survives at the Royal Society, the fair copy made from it to send to Huygens is lost. Huygens sent it to the Abbé Gallois for the <u>Journal des Scavans</u>, but before doing so he copied it in his diary and this version is reproduced by the Halls.(16) The two illustrations are very similar, but they differ in the relative sizes of some parts. In the copy retained by Oldenburg the inner tube has been shown as being as short as the outer tube, whereas in the Huygens version it is considerably longer. The supporting limb was initially shown by Oldenburg with its length divided in half by the mounting pillar, but it has been reduced in length at the eye end so as to support the inner tube below the eyepiece; in the Huygens drawing the limb is symmetrical. The Oldenburg drawing extends to the present right-hand edge of the sheet, and a compression of the drawing on this side may then indicate that it had been begun on the left hand side and that the sheet had proved insufficiently large to accommodate it. The lack of knowledge of the position of the surface of the main speculum in the tube prevents a check of which drawing has the most satisfactory proportions, but it is suggested that the Huygens version may be more representative of the original instrument.

The quality of the mirrors of the telescope is indicated by a few references in the correspondence. While the telescope had still been in Newton's care it had "represented the Moon in some parts of it as distinctly as other Telescopes usually doe wch magnify as much as that."(17) At times however collimation problems gave rise to a poorer image and indicated defects in the figuring.(18) The main mirror had a casting imperfection which showed as "a scabrous place nere the middle of it on ye polished side" and in the course of the grinding of the surface this had naturally affected the local figure.(19) The alloy used was susceptible to tarnishing, and Newton noted this once having occurred "in 4 or 5 days of moist weather".(20) By mid-Match 1672 the performance of the telescope had certainly been affected by tarnishing (or a disturbance of the optical arrangement), but unfortunately the letter describing its condition is lost.(21) The size of the main mirror has already been discussed in connection with Newton's first telescope. It is clear that the diameter was about 2 inches, but there is some doubt about the thickness of the mirror. In the undated manuscript account of the casting of specula already cited, and supposed by Turnbull to be of about 1671/2, Newton described the mirrors of this size as being "about a quarter of an inch thick" in order to "prevent even the slightest bending in the process of grinding and polishing".(22) In the Opticks he more cautiously claimed they were "about one third part of an Inch thick".(23) Newton's reported methods of casting and grinding the metal specula are discussed in a subsequent section.

Notes and References

1. Turnbull (1959), 96: letter of Newton to Oldenburg, 6 February 1671/2.
2. Roy. Soc. MS LXXXI 'Commercium Epistolicum', item 13: draft letter of Collins to Vernon, 26 December 1671.
3. Turnbull (1959), 75, in translation.
4. *Ibid*, 73: letter of Oldenburg to Newton, 2 January 1671/2.
5. *Ibid*, 79: letter of Newton to Oldenburg, 6 January 1671/2.
6. *Idem*.
7. *Ibid*, 76, in translation.
8. See above, ref (5).
9. Newton (1704) I, 75.
10. Hall & Hall (1971), 130: translation of enclosure with letter of Oldenburg to Huygens of 15 January 1671/2.
11. See above, ref (5), and discussions in following section.
12. Turnbull (1959), 80: letter of Newton to Oldenburg, 6 January 1671/2.
13. See the discussion 'Speculum Metal Telescopes' under 'Subsequent Work by Newton' below.
14. Turnbull (1959), 120: letter of Newton to Oldenburg, 16 March 1671/2.
15. See above, ref (12).
16. Hall & Hall (1971), 471, 473 note.
17. Turnbull (1959) 122: letter of Newton to Oldenburg, 19 March 1671/2.
18. *Ibid*, 120.
19. *Ibid*, 122.
20. *Ibid*, 121.
21. Oldenburg's lost letter of 16 March 1671/2 is referred to in Newton's reply of 19 March: *idem*.

22. <u>Ibid</u>, 86-7, in translation.

23. Newton (1704) I, 77.

3.4c Reaction to Newton's Telescope

To the Royal Society, Newton's telescope invention and his doctrine of light appeared as separate issues: one an exciting instrumental advance of likely practical value, the other a stimulating philosophical proposal at variance with current thinking. For Newton, in seeking acceptance for his views, there became no distinction between the two since the telescope merely represented the triumphant proof of his own theory, latterly even playing a symbolic role in ensuring his optical doctrine was unassailable. Z. Bechler, in an analysis of Newton's changing attitude to the practicability of achromatic refraction, has suggested how Newton wished the practical interaction of instrument and theory to be appreciated:-

> "Newton here [in the February 1672 paper on the nature of colour] starts from the accepted premise that contemporary telescopy was deficient, he identifies the true source - unknown till then - of this deficiency by means of his theory of light, predicts its remedy - again by means of his theory - and actually presents the fully constructed new telescope as a proof of the accuracy of his total diagnosis. The new reflector was at once elevated from a mere technological breakthrough - a status by itself high enough to excite wide interest and to lead to his own election into the Royal Society - to that of visible proof of the supremacy of his own theory over the old theories of light." (1)

Initially however the Society did not have the opportunity to judge the telescope against the broader implications of Newton's optical discoveries, since these were submitted only after the telescope had been examined and the Society had adopted a stance that was already largely fixed. The principal feature of the invention was seen to be that it allowed telescopes to be made much shorter but remain as effective. This was no doubt seen as of great significance for observational astronomy where the most powerful instruments had now grown to almost unmanageable lengths and required the very greatest skill in both manufacture and use. The apparently colour-free nature of the image in the reflecting telescope was noted, and it was of course appreciated at the time that chromatic effects limited image quality since it was to reduce these that focal lengths of refractors had to be long and their apertures restricted. However this was seen as an aspect of the general image quality which in turn determined whether or not the new construction was effective. It was thus an unremarkable consequence of the invention itself rather than its central feature.

By the time the formal description for Huygens was drawn up Oldenburg was terming the discovery the "new invention of Isaac Newton ..., whereby long telescopes are considerably reduced in length without impairing the effectiveness of their use."(2) There is no hint here that Newton has discovered how to avoid completely a basic but long tolerated fault of telescopes: the invention is merely sufficient to diminish the telescope's size without degrading image quality still further. Even after Newton's optical theory had been widely discussed the invention was still invariably described as one of 'shortening telescopes'.

Newton's theory of the nature of light and colour had been developed in detailed mathematical form in his Lucasian lectures and the amplified and polished version of these was at that time being prepared for publication as his Lectiones Opticae. Having seen that his telescope had been so warmly received on its own merits, Bechler contends, Newton hoped that this welcome could now be extended to his new theory also.(3) Once he had heard that he had been elected, Newton wrote to Oldenburg asking if he might send in "to be considered of & examined, an accompt of a Philosophicall discovery wch induced mee to the making of the said Telescope, & wch I doubt not but will prove much more gratefull then the communication of that instrument, being in my Judgment the oddest if not the most considerable detection wch hath hitherto beene made in the operations of Nature." (4)

The paper which followed two weeks later[5] was essentially a popular account of the theory of colour, but set within a logical framework designed to gain the Society's more ready acceptance. Lohne in studying how Newton misrepresented the historical perspective of his early optical work concluded of this paper that

"In this narration to the Royal Society he found it opportune to let his theory of colours appear as a Baconian induction from experiments, although it primarily was deduced from speculations." (6)

If however the telescope was to be an effective vehicle for the theory, the achromatic basis of its operation would have to be stressed. Although this link is seen most clearly in Newton's February 1672 paper, it is apparent also in his reaction to Oldenburg's earlier description of the telescope for Huygens. Having made a few factual corrections to Oldenburg's draft, Newton not unreasonably suggested that

"Perhaps it may give some satisfaction to Monsieur Huygens to understand in wt degree it represents things distinct & free from colours, & to know the aperture by wch it admits light." (7)

The colour-free nature of the image had been discussed at the time of the telescope's trial, for it was commented on by Collins and mentioned also by Oldenburg in his initial letter to Huygens. However its significance was lost on Oldenburg who did not follow up Newton's suggestion: the formal description received by Huygens made no reference to the telescope's aperture or achromatic effect and was therefore silent on all its significant and novel optical characteristics.[8]

In the February 1672 paper on colour Newton presented the now familiar series of observations of the effect of prisms, culminating in the experimentum crucis from which he deduced that light was a 'heterogeneous mixture of differently refrangible rays'. Concluding that it was not deficiencies in figuring lenses to theoretical perfection that limited their performance, "which all men have hitherto imagined", but the nature of light itself, Newton took "Reflections into consideration and finding them regular, ... understood that by their mediation Optic instruments might be brought to any degree of perfection imaginable ...".(9)

In Newton's representation in this paper of his telescope as the direct and necessary outcome of the discovery of multiple refractive indices, and therefore of the logical impossibility of focusing white light to a single point by refraction, Bechler finds Newton insinuating clearly

> "that, for all the enthusiasm of its reception, his reflector had been greeted for the wrong reasons, inasmuch as astronomers and optical theorists still mistook the basic source of error in their refractors." (10)

The Royal Society's initial response to the telescope's merits had no such philosophical base, and it has been suggested above that in seeking Royal support for the invention the Society saw a practical or strategic potential, somewhat akin perhaps to that developing for Morland's speaking trumpet. But to realise this potential it had to be demonstrated that the principles and techniques could be extended to larger instruments: only then could it be claimed that the invention was a success. No doubt the Society's aim in embarking on such a development programme was to produce readily manageable instruments of a performance comparable with that of the very long Italian refractors with which J.D. Cassini was having such conspicuous success at the Paris Observatory.

Robert Hooke appears to have begun this work almost immediately since at the first meeting after the recess it was reported:

> "The Curator [Hooke] said, that he did endeavour to make such a Telescope himself, and to find out a Metall not obnoxious to tarnishing." (11)

Two weeks later Hooke's instrument, as yet unfinished but with the impressive focal length of four foot, was being produced at the Society's meeting, and the Fellows in their usual prerogatory manner were ordering him to have it "perfected against [the] next day."(12) For more than a year Hooke, and his associate the optician Christopher Cock, attempted to develop satisfactory large instruments for the Society. In due course general interest waned as the technical problems of working with metal specula proved enduring and Hooke became increasingly diverted by the prospect offered by glass mirrors. In these early months however, the Society's hopes ran high, and Oldenburg wrote enthusiastically to Cassini in January 1672 that the "discovery is obviously of great significance if the result comes up to expectations."(13)

As Curator of Experiments to the Society, Robert Hooke was a salaried officer, charged with providing a stream of demonstrations for the meetings and available to perform all such investigations as the Society thought fit. His efficiency and fertile inventive mind led the Society to expect almost superhuman effort from him, and they depended on him to the extent that his very occasional absence from a meeting would lead to its suspension. Hooke's pivotal role in the Society's experimental programme, however, blurs any distinction that might be drawn between work carried out for the Society, often precipitated by his own comments, and his personal investigations, which were normally conducted under the Society's watchful patronage and as such soon became the Society's concern.

This ambiguous role within the Society conditioned Hooke's response to Newton's discoveries. His initial reaction appears to have been guardedly defensive: Newton had submitted an invention, the novelty of which was not entirely new to Hooke, and the Society was now determined to secure Newton's priority. Hooke attempted to moderate the claims made for the instrument and then, drawing on his earlier experiences with reflecting instruments, he set about to produce a telescope of practical dimensions, no doubt intending a dismissive comparison for Newton's tiny instrument.

Disarmed by the warm reception given to Newton's idea at that first meeting, by the emphasis on the 'shortening' of telescopes, or by the vigorous support planned by the Society on Newton's behalf, Hooke now felt it necessary to defend his own priority in inventing an effective method of shortening telescopes.(14) At the following meeting he submitted a formal 'proposition of a highly considerable Improvement of all sorts of Optick ... glasses' entitled

> "The perfection of Telescopes, Microscopes, Scotoscopes, and burning-glasses, from Lentes of Figures as easily and perfectly made, as plain and Spherical, By which light and apparent Magnitude of Bodies, may be most prodigiously and regularly increased, and whatever almost hath been in notion, imagined or desired in optick, may be performed with great facility and truth." (15)

The substance of this proposition was in the form of a cypher, the explanation of which was given to the President and Christopher Wren, both of whom approved of it.(16) Collins in describing the occasion to Gregory noted that "what is done in this way is performed by

Glasse Refraction."(17)

It seems certain that Hooke was referring to the fluid-filled compound lenses that he had constructed some years before(18), and which are mentioned in an earlier section. His first published account of this type of construction was in the preface of the Micrographia of 1665 where he described the very bright image he obtained when the space between the two principal components of a compound microscope was filled with water.(19) The idea was applied to astronomical telescopes in two notes by Hooke published in the Philosophical Transactions in 1665 and 1666.(20) Objectives were to be constructed from optical components cemented into a cylindrical mount with the intervening space filled with a liquid. By altering the form of the lenses and the type of liquid a whole range of possibilities was opened up. Hooke had apparently used this principle to reduce the length of telescopes as early as 1664 and made the extravagent claim reported by John Collins:

> "that in the yeare 1664 he made a little Tube of about an Inch long to put in his fobb which performes more than any Tellescope of 50 foote long made after the common way, but the Plague happening which caused his absence, and the Fire whence redounded profitable employments about the Cittie, he neglected to prosecute the same being unwilling the Glassegrinders should know any thing of the secret." (21)

The association with his earlier articles seems confirmed by the inclusion in a select list of inventions published by Hooke in 1676 of 'A new sort of Object-Glasses for Telescopes and Microscopes, much outdoing any yet used', described as 'discovered' or published.(22)

In seeking to secure his priority for a general method for perfecting optical systems, and therefore by implication for achieving the effect claimed for Newton's instrument, Hooke undoubtedly felt aggrieved that his own discovery had first appeared in publications firmly associated with the Royal Society and yet not only had it been forgotten by his patrons, they were actively pressing a rival claim.

Hooke may have felt his misgivings confirmed by Newton's arrogant promise of "the most considerable detection wch hath hitherto beene made in the operations of Nature"[23], which turned out to be his theory of colour. The paper was duly received and read at the 15 February meeting where it "mett both with a singular attention and an uncommon applause".[24] It was then referred to three prominent Fellows for review: Seth Ward, perhaps partly in recognition of his role in introducing Newton's work to the Society, Robert Boyle and Robert Hooke. Both Boyle and Hooke had written on the nature of colour and their work was well known to Newton.[25] Hooke, already established as the most original optical experimentalist of his day, is the only one known to have responded, and he produced a detailed critique which was read to the Society the following week.[26]

Whilst praising and confirming Newton's experimental results, Hooke found himself sharply at variance with Newton's conclusions. Bechler sees Hooke, totally unaware of the rigorous mathematical background of the new theory, provoked by Newton's air of dogmatic certainty into critical response.[27] Shapiro, in discussing the difficulties in explaining Newton's "casual but bold form of presentation", finds this linked to a developing overconfidence in the principle of the immutability of colour and degree of refrangibility. Whereas in the earlier formulation of his optical doctrine in his Lucasian lectures each step in the argument had been fully supported by experiments, in the synopsis presented to the Society Newton found it necessary to appeal to only a limited range of experiments and placed the burden of evidence for his interpretation on the single experimentum crucis.[28] Newton misjudged the reaction that this departure from the methodological emphasis on experimental history would provoke. Although Hooke was ready to admit that Newton's theory was adequate to account for his experimental results he claimed that Newton had performed too few experiments to justify his theory, which was therefore not a necessary consequence of the experiments. Not only was there another theory (Hooke's) that could account for the experiments, there were other experiments that could not be explained by Newton's theory.[29]

The theme of Hooke's reply to Newton's paper became an attack on the necessity of Newton's theory: and whereas his criticism of theoretical aspects of Newton's work was not directly effective[30], he was on more secure ground in attacking the technical problems raised by the new telescope. Specifically, Newton had appeared to claim that it was necessary to abandon refractors in favour of reflectors in order to avoid the otherwise unsurmountable effects of chromatic aberrations. Hooke, convinced that his compound lens had the potential to overcome the chromatic difficulty also, wrote:

> "I am a little troubled that this supposition should make Mr Newton wholy lay aside the thoughts of improving telescopes and microscopes by Refractions, since it is not improbable, but that he that hath made soe very good an improvement of telescopes by his own tryalls upon Reflections, would, if he had prosecuted it, have done more by Refraction. And that Reflection is not the only way of improving telescopes, I may possibly hereafter shew some proof. The truth is, the Difficulty of Removing that inconvenience of the splitting of the Ray and consequently of the effect of colours, is very great, but yet not insuperable." (31)

Having questioned the whole deductive basis of Newton's paper and reduced his theory to "an hypothesis", Hooke proceeded to dismiss the originality of Newton's telescope and of the reflecting microscope design he had casually proposed in the course of his paper. Not only had Hooke considerable practical experience of both types of instrument, his experience with reflecting telescopes had actually led him to take the opposite course to Newton and turn from reflecting to refracting systems, developing a powerful new theory for lens construction which had already shown its value in his microscopes:

> "I have made many tryalls both for telescopes and microscopes by Reflection, which I have mentioned in my Micrographia; but deserted it as to telescopes, when I considered, that the focus of the spherical concave is not a point, but a line, and that the Rayes are less true Reflected to a point, by a conçave, than Refracted by a convex; which made me seek that by Refraction, which I found could not Rationally be expected from Reflection; nor indeed could I find any effect of it by one of six foot Radius, which about 7 or 8 years since Mr Reive made for Mr Gregory wth wch I made several tryalls: but it now appears that it was for want of a good encheira; from which cause many good expts have been lost: both which considerably discouraged me from attempting further that way, especially since I found the Parabola much more difficult to describe then the Hyperbola or Ellipsis. And I was wholly taken from the thoughts of it by lighting on divers ways, which in theory could answer all that I could wish for: though having much other business I could not attend to bring them into use for telescopes, though for microscopes I have for a good while used it." (32)

Although the reference to reflecting optics in the Micrographia is the briefest[33], Hooke was drawing attention to what appeared to him as Newton's superficial familiarity with the work. Several of the experiments appealed to by Newton had previously been described by Hooke (although Newton credited only one, which was to be found "somewhere in his Micrography") and yet Newton had failed to take adequate account of Hooke's work in both reflecting optics and interference colouration. Newton's debt to the Micrographia is now appreciated from his youthful manuscript notes, but unfortunately these do not include comments on the volume's preface which dealt with instrumental points.[34]

Hooke's critique clearly caused embarrassment to the Society. Oldenburg had been instructed to write immediately to Newton to ask permission to publish his paper, and this he proposed to do in the issue of the Philosophical Transactions that was shortly to be printed.(35) Newton's letter thanking the Society for its fulsome praise and readily agreeing to publication was received two days before Hooke's swingeing attack on Newton's methodology was presented.(36) Newton's only reservation about publication had been that supporting experiments had been omitted "to shun tediousnesse", and this very paucity of detail turned out to be a principal plank in Hooke's objection. Hooke was dryly thanked for his "pains in bringing in such ingenious reflections" and Oldenburg was instructed to send a copy immediately to Newton, who might now not wish his own paper published. Hooke's review was certainly not to be published at present,

> "it not being thought fit to print them together, lest Mr. NEWTON should look upon it as a disrespect, in printing so sudden a refutation of a discourse of his, which had met with so much applause at the Society but a few days before." (37)

In fact Oldenburg's letter was not dispatched until immediately before the issue of the Philosophical Transactions closed for press; but Newton did not seem concerned, and his reply promising that Oldenburg would "very suddenly have my answer" to Hooke's criticisms is written with the same confident certainty as his earlier paper.(38)

The 'sudden' answer however took four months to materialise, and from an examination of the several surviving drafts of the reply Bechler has concluded that:

"Dubious as the evidence is for Newton's researching into the theory of an achromatic compound lens before February 1672, it is very clear that, during the next four months, between his reading of Hooke's 'admonishment' and his writing of the final answer to it, Newton came positively to believe in the feasibility of such a lens." (39)

But by pursuing this line Newton would have weakened the case for his reflecting telescope and therefore for his new theory of colour, and so he was to discourage such discussion in the final version sent to the Society. In an acid preamble to this Newton pointed out that he had only dispaired of improving "ordinary" telescopes, but not of "other constructions":

"For although successive refractions wch are all made the same way, doe necessarily more & more augment the errors of the first refraction; yet it seemed not impossible for contrary refractions so to correct each others inequalities, as to make their difference regular, & if that could be conveniently effected, there would be no further difficulty." (40)

The implication that such attempts were in fact futile was not supported: Newton stated that he had made experiments and trials for compound lenses but said only that these had been disappointing.(41) Publication of a negative result, Bechler points out, would have demolished Hooke's argument and not detracted from the prestige won by his reflector(42); and so Newton, unwilling to appear to give support to Hooke, merely avoided the issue by saying he "may possibly find a more proper occasion to declare" his results.(43)

In the earliest version(44) Newton gave a clearer description of compound achromatic lenses and claimed that he had already calculated the correct elements for such a lens. This contention is supported by an experiment accompanying this version, which employed a compound prism and provided a most effective refutation of Hooke's modification theory of colour generation in refraction. In this Newton showed that a ray can be refracted by an optical system and yet emerge white, and therefore provided compelling evidence for the possibility of an achromatic lens. The dilemma that emerged from this experiment was that by using it to refute Hooke's theory, and therefore admitting the possibility of an achromatic lens, there was no real reason to despair of refraction and turn to reflection, whereas rejecting this possibility might allow the tenability of Hooke's theory and imply Newton's agreement.(45) Newton's solution was to suppress the experiment, both from his reply to the Royal Society and from the version of his Lectiones opticae later to be deposited in Cambridge University Library.

Bechler has demonstrated how Newton only returned to the suppressed experiment after Hooke's death, publishing it in the Opticks but drawing from it the opposite conclusion to that he had reached in 1672.(46) In thus finally pronouncing the impossibility of achromatic lenses, Newton betrayed the importance that the dispute with Hooke had assumed for him, and the overriding need he had felt to maintain the unassailible necessity of his theory. By now being able to represent the improvement of refractors as completely "desperate" he confirmed the logical necessity of his reflecting telescope as a direct consequence and justification of the theory.(47)

Arguably then, the circumstances of the presentation of this theory and the reaction it provoked had forced Newton into an inflexible defensive position in which the reflecting telescope assumed a central and symbolic role.

Newton's lengthy and unreasonable caustic reply to Hooke's criticism was principally an attack on Hooke's impulse theory and on his attribution of a corpuscular theory to Newton. It exhibited clearly the pronounced neurotic attitude that was to characterise Newton's optical correspondence, described by Kuhn as

"Newton's fear of exposure and the correlated compulsion to be invariably and entirely immune to criticism ... combined [here] with the beginning of that tendency to deny the apparent implications of earlier writings (rather then either defending them or admitting to a change of mind) ..." (48)

The reply was eventually printed in the Philosophical Transactions in November 1672, but in view of its harsh tone it must have seemed a gratuitous insult to Hooke that his own critique was not printed at all. Oldenburg excused this by saying that Newton's reply referred to all the main points that had been raised by Hooke.(49)

Oldenburg's handling of the printing of Newton's optical theory contrasts with the publication of material directly related to the reflecting telescope itself. Rather than wishing to rush into print it is apparent that Oldenburg wished to see the Society's full scale trials come to some successful conclusion before he made the invention public.(50)

Although he had received Newton's permission to publish the description of the telescope at the end of January, as late as 4th March he was writing to René de Sluse only that he would "soon insert an account of the whole thing with a figure of the instrument in my Philosophical Notebooks."(51) However, it was only a partial account that appeared in the 25 March issue. In mid-March the Society was expecting imminent success in its attempts to have a larger instrument constructed, and it is possible that the March issue of the Transactions was delayed by Oldenburg in the hope of including an account of this.(52) In the event, Oldenburg was only able to describe Newton's instrument, adding extracts from several letters received from Newton with further details of construction and use, including a summary of one letter clearly added at proof stage.

By now Oldenburg was also getting reaction to the invention from his correspondents, and in this first issue he was able to print an encouraging response from Christiaan Huygens in Paris, to whom one of the earliest accounts had been sent. Huygens had passed Oldenburg's description of the instrument to Jean Gallois, editor of the Journal des Scavans, and it had appeared in the 19 February issue together with a letter from Huygens, promoting the instrument's merits in much the way the Royal Society had hoped for.(53)

Four particular advantages were seen by Huygens for Newton's "beautiful and ingenious" invention. Firstly, using only spherical surfaces, a concave mirror with the same focal length and aperture as a convex lens would have a smaller degree of spherical aberration.(54) A mirror could therefore operate at a much wider aperture, and support a higher magnification if the focal length was reduced. Secondly, by using a reflecting rather than a refracting system, Newton had avoided "injuring" the rays by their passage through inclined glass faces. Huygens at this time believed that the colouration of the light was due to the inclination of the faces of the lens, and the effect could therefore be minimised by using only the central portion of the lens where the faces were nearly parallel. Huygens was aware that the chromatic effect would be worse for the elliptic and hyperbolic glasses strictly required for eliminating spherical aberration, since the faces of these would be more sharply inclined at their circumferences. The third and fourth advantages were that light was lost by reflection at both surfaces of lenses, and some also affected by the "obscurity of their matter", a comment on the poor optical quality of glass.

If, on the other hand, parabolic mirrors could be fashioned, these should be equivalent in quality to what had been hoped for from refractors with conic section lenses, and because only one surface had to be worked they ought to be easier to realize. The principal problem of course was finding a suitable material which could take the "lively and unified polish" necessary. Although Huygens trusted that this could be achieved, he was privately pessimistic when sending a similar account to his brother.(55) Huygens' letter to Oldenburg was couched in very similar terms, and Newton later joined him in agreeing that it was unlikely that non-spherical surfaces could be produced.(56)

This was however merely the first of a string of comments, often with detailed criticism of Newton's work, which were received by Oldenburg and passed on to Newton for reply. There is no doubt that Newton found this new task of justifying his writings irksome and distasteful, and on more than one occasion he attempted to resign from the Society in order to disengage himself from the seemingly endless discussion of his optical work which was filling the pages of the Philosophical Transactions.(57)

Two early criticisms of the telescope, as opposed to the theory of colour, were received at the end of March from Adrien Auzout and Jean-Baptiste Denis. Auzout, an astronomer and experienced grinder of astronomical objectives, was also a Fellow of the Royal Society, and in recent years had become involved in controversy with Robert Hooke as well as with members of the French scientific community. His letter unfortunately does not survive, but from Newton's reply it can be seen that Auzout was objecting to the low reflectivity of metal surfaces (no doubt contrasted with the efficiency of lenses then being produced by a new technique in Paris[58]) and also the inevitability of this reflectivity reducing as the metal tarnished. The physician and natural philosopher Denis edited a series of scientific Mémoires et Conférences of a group independent of the Académie des Sciences. Newton's telescope had been described by Denis in his third Mémoire[59], in which he had welcomed the invention as one which would free astronomers from the "great embarrassment of machines" that had become necessary for managing the largest refractors. For although astronomers were "well served with masts, ropes, pulleys and other things", telescopes had already reached such length that they were incapacitated by vibration in the wind. Not only did Newton's instrument demonstrate how more manageable telescopes would be produced, these would result in great financial saving, and so better instruments could be afforded.

Denis in his letter to Oldenburg had apparently been concerned to know how the aperture and focal length of mirrors were to be related, and to know whether the secondary mirror would exclude too much light. Newton had already developed a table relating focal length, aperture and magnification for instruments up to twentyfour feet, and this appeared in the April issue of the Philosophical Transactions alongside Newton's reply to Auzout and Denis.[60] The relationship had apparently been derived by considering the size of the circle of minimum spherical aberration and assuming that the size of the image on the retina, and its illumination, should be constant.[61]

Potentially more damaging to the instrument was Auzout's criticism of metal reflecting surfaces. Whilst attempting to brush these difficulties aside by stressing that the search for suitable alloys and techniques was not yet complete, Newton nonetheless devoted much of his prompt reply to ways of avoiding the degrading effects of tarnishing. In doing so his concern is clearly seen that the acceptance of his instrument, and by implication his new optical theory, should not be jeopardized by a failure to meet technical requirements. The instrument had been designed to demonstrate a principle, and was being used to justify a concept; yet it was being judged on tiresome technical detail which to Newton missed the point at issue. His reaction however recognised the need to provide effective practical solutions to such objections, and his specific proposals, which are discussed in a later section, included the first mention of a reflecting prism to replace the flat secondary mirror.(62)

An immediate effect of the publication of Newton's invention was to encourage others to imitate him. The prominent position that Oldenburg gave to it in his <u>Philosophical Transactions</u> and in his extensive correspondence, together with his brief but optimistic references to the Royal Society's attempts to improve on the instrument, ensured widespread interest in the new instrument, and stimulated a number of attempts to construct it. Thus, in September 1672 Oldenburg was able to write to Newton with news of a small reflecting telescope that had been made in Florence by Pietro Salvetti "by wch you see, that your productions are spred further than perhaps you are aware of".(63)

It was in Paris however that the most concentrated efforts were made. The appearance of the account in the <u>Journal des Scavans</u> was followed immediately by a report from Paris that "They are see[ing] at the Royal Academie what innovations may bee made in Mr Newton's Telescope."(64) These efforts do not seem to have been blessed with immediate success for about two months later Cassini was wishing they had "some outstanding craftsmen (such as you have) ... for ours have so far been able to accomplish nothing noteworthy in this matter."(65) There are also scattered references in Huygens' correspondence to his own attempts to construct a reflector, but in late June 1672 he was reporting failure.(66) Huygens had used a bronze alloy which had proved so soft that the act of polishing the surface had ruined the spherical figure that he had ground. The mirror, four inches diameter but with the very long focal length of twelve feet, had been ground on a tool of the same material, and Huygens had been dismayed to find that his glass polishing technique was useless for this metal. It is unclear whether he conducted further experiments, or whether he was referring to this attempt when he wrote to his father in 1674, saying that there was a

> "great obstacle in this manner of telescopes, vz the softness of the metal in comparison of Glasse, wherefore it doth not receive so perfect a polishing neither is it able to keep it, so that I hope but little of it, for practice". (67)

Beyond this initial excitement of activity caused by Newton's telescope, the only development of interest to emerge from Paris was the publication in May 1672 of a proposal for a new form of reflecting telescope designed by a Mons. Cassegrain. This proposal, which is discussed in a subsequent section(68), was seen at the time as a direct response to the announcement of Newton's invention, since priority was claimed on Cassegrain's behalf. It received a highly critical review from Huygens and the claim was not pressed.

<u>Notes and References</u>

1. Bechler (1975), 103.
2. Turnbull (1959), 75, in translation.
3. Bechler (1975), 103.
4. Turnbull (1959), 82: letter of Newton to Oldenburg, 18 January 1671/2.
5. Ibid, 92: letter of Newton to Oldenburg, 6 February 1671/2.

   It is not known if Oldenburg encouraged him to send this when he wrote on 20 January, but Oldenburg was instructed to do so at the Society's meeting on 25 January, and so Newton may only have been asked to proceed in Oldenburg's letter of 27 January.
6. Lohne (1965), 138.
7. Turnbull (1959), 79: letter of Newton to Oldenburg, 6 January 1671/2.
8. Possibly this reflects Oldenburg's lack of understanding of the device since this was the only proposed alteration for which Newton did not provide an appropriate form of words for the change.

   Equally it may have been an oversight since an insertion was made in the version published by Oldenburg in the Philosophical Transactions in March. Even here however Oldenburg's limitations are apparent, and it must have pained Newton to see the inadequate insertion made a logical absurdity by coupling it with another of his suggested additions about magnification:

   > "And to give the Reader some satisfaction to understand, in what degree it represents things distinct, and free from colours, and to know the aperture by which it admits light; he may compare the distances of the focus E from the vertex's of the little Eye-glass and the Concave speculum, that is EF, 1/6 of an inch, and ETV, 6 1/3 inches; and the ratio will be found as 1 to 38; whereby it appears, that the Objects will be magnified about 38 times."

   Phil. Trans. R. Soc. Lond. 7 (1672) 4005. This was contained in Issue 81, which will have been received by Newton shortly after 10 April.

9. Turnbull (1959), 95: letter of Newton to Oldenburg, 6 February 1671/2.
10. Bechler (1975), 103.
11. Roy. Soc. MS Journal Book, meeting of 11 January 1671/2.
12. Ibid, meeting of 25 January 1671/2.
13. Hall & Hall (1971), 477: translation of Oldenburg to Cassini, 15 January 1671/2.
14. Collins claimed that Hooke was prompted by "seeing this [i.e. Newton's] Tellescope to obtain esteeme": enclosures with letter of Collins to Gregory, 23 February 1671/2, Turnbull (1939), 222.
15. Roy. Soc. MS Journal Book, meeting of 18 January 1671/2.
16. "The president ... said, that he had not yet had time to examine it well; but by what he had seen, he could not but have a good opinion of it. This was seconded by Mr. Surveyor Dr. Wren, who had also been made acquainted with it by the Inventor". Ibid, meeting of 25 January 1671/2.
17. Turnbull (1939), 223: enclosure with letter of Collins to Gregory, 23 February 1671/2.
18. One reference which does not appear to support this is a memorandum by David Gregory of 5 July 1708 (Hiscock (1937), 42):

> "Mr. Waller who published Dr. Hooks posthumous works has found his microscope and the resolution of the cypher concerning it. He is to publish it. The effects of the microscope are supprizing: it takes in so large an angle. It is catoptical".

Richard Waller's Posthumous Works of Robert Hooke was published in 1705. Waller received a number of items, including the MS diary, from Hooke's niece in 1708 but did not publish these before his death in 1714, when they passed to William Derham. It is possible that Hooke's 1672 proposition was sufficiently allembracing to include reflecting systems, but it is more likely that this microscope and the cypher were not connected.

19. Hooke (1665), preface, $F1^v - F2^r$.
20. Phil. Trans. R. Soc. Lond. 1 (1665-6) 63-73, Issue 4, dated 5 June 1665; ibid, 202-3, Issue 12, dated 7 May 1666.
21. Turnbull (1939), 223: enclosure with letter of Collins to Gregory, 23 February 1671/2.
22. Hooke (1676), 31.
23. Turnbull (1959), 83: letter of Newton to Oldenburg, 18 January 1671/2.
24. Ibid, 107: letter of Oldenburg to Newton, 8 February 1671/2.
25. Lohne (1965), 130, has demonstrated Newton's debt to Boyle's Experiments and Considerations Touching Colours (London 1664).
26. Birch (1756-7) III, 10.
27. Bechler (1975), 104.
28. Shapiro (1980), 214.
29. Kuhn (1958), 37.
30. Hooke however was correct in claiming that Newton's corpuscular theory could not explain the colouration effects of thin films previously described in his Micrographia (pp 47-67). Newton in his revised theory of 1675-6 had to introduce an aethereal medium to account for these.
31. Turnbull (1959), 111: manuscript by Hooke, undated but read to the Royal Society 15 February 1671/2.
32. Ibid, 111-2. Hooke's work has been passed over in studies of the reflecting microscope. Thus Bradbury (1968) makes no mention of it and credits Barker with the construction of the first instrument in 1736. However, the truth of Hooke's claim

to have made such instruments is confirmed by Waller's discovery of one, reported by David Gregory (Hiscock (1937), 42), which Waller subsequently produced at a meeting of the Royal Society: "Mr Waller shew'd a Reflecting or Catadioptrick Microscope, which he found amongst ye late Dr. Hooke's Optic Glasses, and told ye President ye Proportions of ye Radius of ye two spheres, which were to each other as 2 to 3, the innermost being two, ye outermost three, the Object placed nearly Parallel.": Roy. Soc. MS Journal Book, meeting of 5 April 1711. Remotely, this particular microscope may have been made after 1672 since there is an isolated reference "Tryd reflex microscope" in Hooke's diary for 6 February 1673/4: Robinson & Adams (1936).

33. Hooke (1665), preface, $F2^r$: "I have made a Microscope with one piece of Glass, ... divers also by means of reflection."

34. Keynes (1960), 97: Appendix IV. Transcribed from U.L.C. MS Add 3958.I.I.

35. Birch (1756-7) III, 9: meeting of 8 February 1671/2. Turnbull (1959), 108: letter of Oldenburg to Newton, 8 February 1671/2. The principal reason given for seeking an immediate printing was (as with the telescope) that "the ingenuous & surprising notion therein ... may easily be snatched from you, and the Honor of it be assumed by forainers" (Turnbull). Without doubt the Society's precipitate and uncritical decision to champion Newton's theory "against the pretensions of others" (Birch) will have rankled with Hooke, and to some extent blame for the bitter dispute that ensued must rest with the Society for declaring its intentions so early.

36. Turnbull (1959), 108: letter of Newton to Oldenburg, 10 February 1671/2, endorsed as received on 13 February.

37. Birch (1756-7) III, 10.

38. Turnbull (1959), 116: letter of Newton to Oldenburg, 20 February 1671/2. Newton dated Oldenburg's letter as 19 February but this was the date of receipt not dispatch, which was the 17th. Issue 80 of Phil. Trans. was dated 19 February.

39. Bechler (1975), 109.

40. Turnbull (1959), 172: letter of Newton to Oldenburg, 11 June 1672.

41. Idem: "... my successes in the tryalls that I have made ... I shall now say have been lesse then I sometimes expected, & perhaps lesse then he [Hooke] at present hopes for".

42. Bechler (1975), 110.

43. Turnbull (1959), 172: letter of Newton to Oldenburg, 11 June 1672.

44. U.L.C. MS Add 3970, ff433^r - 444^v, identified as version 'A' by Turnbull (1959), 191 n20: discussed by Bechler (1975), 112-6.

45. Ibid, 122.

46. Idem. A less satisfactory interpretation, with a brief discussion of earlier work is provided by Kuhn (1958), 41 n24.

47. Newton (1704) I, 75.

48. Kuhn (1958), 39.

49. Phil. Trans. R. Soc. Lond. 7 (1672) 5084, Issue 88, dated 18 November 1672: "Which Discourse [Hooke's] was thought needless to be here printed at length, because in the body of this Answer are to be met with the chief particulars, wherein the Answer was concern'd."

50. The progress of these trials is described in the section 'Telescopes by Robert Hooke and Christopher Cock' below.

51. Hall & Hall (1971), 575: letter of Oldenburg to Sluse, 4 March 1671/2.

52. Issue 82 closed for press on the fourth, rather than the usual third, Monday of the month.

53. Gallois (1672), 23-28: Issue dated 29 February 1672, N.S. (19 February, O.S.).

54. Huygens calculated that the spherical aberration of the lens was about ten times that of the mirror: Huygens (1897), 131-2.

55. Ibid, 139: letter of Huygens to Constantine Huygens, 1 February 1671/2: "Londoners are seeking a method of imparting a good polish, but I doubt if they will find it in the end."

56. Turnbull (1959), 89-91: letter of Huygens to Oldenburg, 3 February 1671/2, ibid, 116: letter of Newton to Oldenburg, 20 February 1671/2.

57. Whiteside (1969), xvii n29; Turnbull (1959), 149 n7.

58. Hall & Hall (1971), 520: letter of Huygens to Oldenburg, 3 February 1671/2.

59. Denis (1672), 43-9: Issue dated 1 March 1672, N.S. (20 February, O.S.).

60. Turnbull (1959), 124: letter of Newton to Oldenburg, 26 March 1672.

61. Ibid, 126 n9.

62. Turnbull (1959), 126-8: letter of Newton to Oldenburg, 30 March 1672.

63. Hall & Hall (1973), 186: letter of Platt to Oldenburg, 27 July 1672.

64. Hall & Hall (1971), 586: letter of Vernon to Oldenburg, 27 February 1671/2.

65. Hall & Hall (1973), 24: translation of letter of Cassini to Oldenburg, 13 April 1672. In March there had been an indication that a London-made reflector would shortly be sent to France; Hall & Hall (1971), 585: letter of Oldenburg to Huygens, 11 March 1671/2. For other suggestions of a very limited commercial manufacture in London at this time see the section 'Telescopes by Robert Hooke and Christopher Cock'.

67. Huygens (1897), 392: letter of Huygens to Constantine Huygens (father), 7 August 1674 (Quoted by van Helden (1976), 49 n61).

68. See the section 'Cassegrain's Proposal and the Debate over Optical Systems'.

66. Hall & Hall (1973), 119: translation of letter of Huygens to Oldenburg, 21 June 1672 (O.S.).

3.5 A THIRD TELESCOPE ATTRIBUTABLE TO NEWTON

During the months following the submission of Newton's telescope to the Royal Society there was a lively correspondence between Newton and Oldenburg on practical matters such as the composition of speculum alloys. The Society's Curator, Robert Hooke, and the optical worker Christopher Cock, were actively involved in producing large reflectors for the Society, and Newton himself was engaged in further work. In a letter of 16 March 1672 he told Oldenburg that "One of the Fellows of our College is making another such Telescope". Although as yet unfinished, it gave "distinct & sharply defined" images and he promised to send a careful assessment of its performance, adding that "it seems to be something better than that wch I made".[1] It has been suggested that the maker was John Wickins (?1644-1719), who at the time shared rooms with Newton and acted as his amanuensis.[2] This attribution is supported by a memorandum by David Gregory dated 1694:

> "Mr Newton found ane excellent Chimical Mixture for Mettallins not to tarnish, but his Chamber-fellow one Wickins a parson in Hereford made one by Mr Newtons direction which is admirable". (3)

It appears however that the alloy was cast by Newton himself, since in a discussion of alloy composition in January 1672 he had noted that

> "At another time I mixed Arsenick ℥ i Copper ℥ vi and Tin ℥ ij. And this an Acquintance of mine hath polished better then I did the other". (4)

The performance of the telescope was, as promised, described to Oldenburg a few days later, when Newton referred to the telescope only as "another instrument made like the former wch doth very well". He compared it favourably with a six-foot refractor, and its resolution was such that he was able to

> "reade in one of the Philosophicall Transactions placed in the sun's light at a hundred foot distance, & that at a hundred & twenty foot distance I could discover some of the words". (5)

His suggestion that the Philosophical Transactions be used as a convenient standard resolution chart seems to have been adopted, and this test remained in popular use for some time.[6]

The only known physical characteristic of the instrument is its effective aperture of $1\frac{1}{3}$" defined by an eyepiece stop[7] and measured by an occlusion test.[8] Further details of the telescope were included in a letter from Newton dated 26 March, and it appears from this that he was completing the figuring of the instrument himself:

> "the little piece of metall next the eye glasse is not truely figured; whereby it happens that objects are not so distinct at the middle as at the edges. And I hope that by correcting the figure (in wch I find more difficulty then one would expect) they will appeare all over distinct ..." (9)

Shortly after sending this, Newton received from Oldenburg the queries posed by Adrien Auzout and Jean Denis discussed in the previous section. In his reply Newton described a number of features of "a Tube of six inches".[10] Its effective aperture, limited by an eye-stop, should be $1\frac{1}{4}$" or $1\frac{1}{3}$" and "it is convenient that the Tube be a little wider then that aperture precisely requires suppose $1\frac{1}{2}$ or $1\frac{2}{3}$ of an inch, & not more". The diameter of the primary however "should not be lesse than two inches because its figure towards the edges will scarcely be so true as to be useful." The minor diameter of the secondary should be between $\frac{1}{3}$" and $\frac{1}{4}$". Although his comments were intended to relate to instruments of this size in general, the specific dimensions are clearly based on experience and may well refer to the telescope then in his care.

In the following discussion this telescope will be referred to as

Newton's 'third' telescope: the justification for this being that Newton was actively involved in its construction, and latterly appears to have considered it at least partly his own work.(11)

The account of Newton's early work on reflecting telescopes published in his Opticks of 1704 is historically confusing: in part this is because he has coalesced his experiences with several similar instruments, but also because he has chosen to simplify them. The physical description of the telescope however tallies fairly well. The primary metal was spherically concave to a diameter of 25" giving the instrument a length of about $6\frac{1}{4}$ inches, and the eye-lens was plano-convex, to a spherical diameter of just under 1/5 inch. The consequence of these physical characteristics was that "it magnified between 30 and 40 times", whereas by "another way of measuring I found it magnified about 35 times".(12) This second method is presumably the one used by Newton in his letter to Oldenburg of 6 January 1672, where he was able to deduce the magnification of his second instrument, which had been compared in performance with a 2-foot Galiliean telescope by the Royal Society.(13) The calculation had been included by Oldenburg in the original description of the telescope published in the Philosophical Transactions.(14) By increasing slightly the focal length of the eyepiece and indicating a range of magnifications, Newton was bringing his description into line with his later admission (under criticism) that the magnification of the instrument had been too high. This had been contained in a letter published in the following issue of the Philosophical Transactions, in which he had recommended magnifications in the range 32-40 times depending on the brightness of the objects to be observed, but had cited as an example, to illustrate a table of preferred dimensions for telescopes, a six inch instrument with a magnification of only 30 times.(15)

The performance of the telescope described in the Opticks was such that by "comparing it with a pretty good Perspective of four Feet in length, made with a concave Eye-Glass, I could read at a greater distance with my own Instrument than with the Glass".[16] Newton first appears to have tested resolution by reading type at a distance with the third instrument, in March 1672, and again the description of this test was published by Oldenburg: on this occasion he also compared the resolution of the reflector with that of a refractor, although the instrument had a length of 6 feet rather than 4 feet.[17] However the comparison with the 6-foot telescope was unsatisfactory in that Newton came to the conclusion that it was not of a sufficiently high quality: "I find that the other (wch I borrowed to make the comparison) to be none of the best in the kind".[18] Newton, realising that Oldenburg would publish this comment, later felt constrained to moderate his criticism "least the freind of whome it was borrowed should think I depreciate it", and in the published version reliance is placed solely on the reading test of resolution.[19] It seems likely that Newton subsequently decided that the reflector would have performed well against a good 4-foot refractor, using this as the comparison in the Opticks, although it is not known whether such a test was actually carried out. Newton continued, in terms very similar to those he had used in his discussion of the third telescope, by suggesting that the instrument would have operated more satisfactorily had the magnification been even lower, again underlining his concern that the instrument should not be challenged on its technical performance.[20] The physical features of the telescope as recalled in the Opticks were thus readily reconstructable from the early published account.

The account in the Opticks continued by describing how two instruments had been constructed according to this design:

> "Two of these I made about 16 Years ago, and have one of them still by me, by which I can prove the truth of what I write. Yet it is not so good as at the first. For the concave has been divers times tarnished and cleared again, by rubbing it with very soft leather". (21)

It has been previously assumed that these two instruments were the first (1668) and second (1671) telescopes, from which it follows that it was the first instrument that had remained with Newton.[22] However an alternative interpretation is that Newton was referring to the second and third (1672) telescopes.

The evidence for this suggestion must be considered largely circumstantial. Newton blamed "bad Materialls" and the "want of Good Pollish" for the disappointing performance of the first telescope[23], whereas the second was "sensibly better than the first".[24] He was actively engaged in experiments to find alloys with improved properties in 1671[25] from which it seems reasonable to assume that the early alloys were less satisfactory and may have been liable to tarnish. The first telescope is only referred to once in the correspondence with the Royal Society, and its performance is only noted in the past tense.[26] The lack of any further mention suggests that, although the telescope may perhaps still have existed, it was not by that time serviceable. Had the mirrors subsequently been re-polished the telescope would clearly have been inferior to the instrument begun by Wickins, and it would hardly seem worthwhile re-figuring the early specula when newer alloys were being developed. Yet the telescope that was in Newton's possession when he wrote the <u>Opticks</u>, although re-polished on a number of occasions, was still of sufficient quality to "prove the truth" of his statements about the optical performance of his reflectors, and these, as has already been mentioned, appear to be based on the measured performance of the third instrument. On this basis the third instrument is a more plausible choice for the instrument described in the Opticks.(27)

A possible internal check is provided by dating in the Opticks. The volume is divided into three books. In the first of these, which is the development of his February 1672 paper, Newton demonstrated the compound nature of white light and dealt generally with colours produced by refraction. The first part of this book contains his discussion of reflecting telescopes. Book II is largely concerned with colours generated in what we now recognise as thin film interference, and is based closely on a lengthy paper composed in 1675 for the Royal Society and read over several meetings in late 1675 and early 1676. Book III begins with observations of diffraction effects, and the volume is concluded with a series of 'queries' for further investigation, posed because Newton had been "interrupted" (by the work of the great re-coinage at the Mint) and did not feel able to pursue them himself. In the Advertisement to the Opticks Newton made clear the separate origins of the three books:

> "PArt of the ensuing Discourse about Light was written at the Desire of some Gentlemen of the ROYAL-SOCIETY in the Year 1675 [i.e. Book II, pts I-III]. and then sent to their Secretary, and read at their Meetings [in early 1676], and the rest [i.e. Book I] was added about Twelve Years after [i.e. "about" 1787-8] to complete the Theory; except [for Book III and Book II, pt IV] ... which were since put together out of scattered Papers." (28)

Book I of the Opticks had its origins not in the 1674 Opticae lectiones but in an apparently unfinished treatise titled Fundamentum opticae, the folios of which are now scattered amongst Newton's optical manuscripts.(29) Newton abandoned this treatise after his failure to prove the proposition that heterogeneous rays are unchanged by refraction, deciding to revise and rewrite it in English; and

Shapiro has recently described how "about half the present Book I of the Opticks is actually a revised, rather literal translation of the Fundamentum opticae, which thus became a first draft of the Opticks."(30) He has traced the evolution of certain propositions through the various drafts of the early 1690s and has demonstrated that substantial modification was still being made in about 1694.(31) In May 1694, however, Newton allowed David Gregory to see his "Three Books of Opticks" and Shapiro concludes from the description given that they were by then essentially completed.(32) Newton's reference to Book I having been "added about Twelve years after" must then relate to the beginning of his work on this book, and thus perhaps to the preparation of the Fundamentum opticae.(33) The section of Book I in which his early work on reflecting telescopes was described (Part I, Proposition VII) is not included in the Fundamentum opticae but was added later, apparently as is suggested above by recourse to his published February 1672 paper.(34) Nonetheless, it includes one of the few dateable points in Book I(35), and the date has clearly been adjusted to be consistent with the claimed date of writing, namely "about" 1687-8. Newton stated rather precisely that he had made "Two of these" small metal speculum reflectors, as described above, "about 16 Years ago". Bearing in mind that the published version of his 1672 paper would remind him that his first instrument had been produced some years before the telescope sent to the Royal Society, it is significant that the instruments are described as having been produced at the same time. The second and third telescopes were however constructed within a few months of each other in late 1671 to early 1672, so that one would infer that a comment that they had made about 16 years before would have been written "about" 1687-8.

A confusing picture however is presented in the short memorandum written by David Gregory and cited earlier. In this, Gregory recorded comments made by Newton's young and ardent disciple Nicholas Fatio de Duillier (1664-1753) when he met the latter in London in May 1694:

> "Mr Newton has spoiled the Mirroir of his telescope with his Hand. the Hand tho apparently sure is able to leave furrows in a Metallin. Mr. Newton found ane excellent Chimical Mixture for Mettallins not to tarnish, but his Chamber-fellow one Wickins a parson in Hereford made one by Mr Newtons direction which is admirable. He now has the telescope that is excellent." (36)

There is no information in Newton's published correspondence as to whether the mirror of the third telescope was more or less likely to tarnish than others, although it does appear to have been more competently figured. It is not clear whether Gregory is saying that Wickins made a speculum alloy which was admirable rather than excellent in its likelihood of not tarnishing, or whether Wickins made an admirable mirror using Newton's excellent non-tarnishing alloy. The latter interpretation is consistent with Newton's comment at the time to Oldenburg.(37) Similarly, it is unclear whether, in the last line, he (presumably Newton) has a telescope that performs excellently or one that has specula of the excellent alloy: certainly it was one that had become excellent in his hands since he had completed the figuring. In any event, this instrument can hardly be the first made by him, since this was certainly superseded in quality by the later instruments, but must be the third. Remotely it might be a further instrument unrecorded in the surviving correspondence and necessarily constructed at a later date. It is perhaps fruitless to read too much into such a second-hand account. However it is noticeable that the name of John Wickins is introduced in a very clear way, indicating perhaps that Newton wished to acknowledge Wickins' contribution to the instrument. The implication then is that the third instrument remained with Newton until at least 1694, but that the primary mirror may have become unserviceable at this time.

Thus it appears that by postulating that this third instrument should be considered as Newton's, a reasonably self-consistent interpretation can be placed on the seventeenth-century references to the Newton reflectors.

Notes and References

1. Turnbull (1959), 121: letter of Newton to Oldenburg, 16 March 1671/2.
2. See, for example, Hall & Hall (1971), 591.
3. Turnbull (1961), 355.
4. Turnbull (1959), 84: letter of Newton to Oldenburg, 29 January 1671/2.
5. Ibid, 122: letter of Newton to Oldenburg, 19 March 1671/2.
6. See, for example, the comparisons between various small reflectors conducted by John Bevis, George Graham and others in 1736: Roy. Soc. MS Letter Book LBC.23.88.
7. See above, ref (5).
8. Turnbull (1959), 124: letter of Newton to Oldenburg, 26 March 1672.
9. Idem.
10. Ibid, 128: letter of Newton to Oldenburg, 30 March 1672.
11. The proposal was outlined to A.A. Mills who has introduced it in his recent paper: Mills & Turvey (1979). Previous commentators have considered only the two familiar instruments.
12. Newton (1704) I, 75. The eyelens described would lead to a magnification of around 31 times.
13. Turnbull (1959), 79: letter of Newton to Oldenburg, 6 January 1671/2.
14. Phil. Trans. R. Soc. Lond. 7 (1672) 4006, Issue 81, dated 25 March 1672.
15. Ibid, 4032-3, Issue 82, dated 22 April 1672, printing Newton's letter to Oldenburg of 26 March 1672 which had been previewed in a late insertion in the previous issue, p4010.
16. Newton (1704) I, 75-6.

17. Turnbull (1959), 122: letter of Newton to Oldenburg, 19 January 1671/2: "Yesterday I compared it with a six foot Telescope ... And to day I found that I could reade in one of the Philosophicall Transactions ... at a hundred foot ...". The implication of Newton's comments is that he had not used this resolution test before and certainly no comparable performance figures were given for the second telescope.
18. Turnbull (1959), 123: letter of Newton to Oldenburg, 26 March 1672.
19. Ibid, 138: letter of Newton to Oldenburg, 13 April 1672. The amended letter of 26 March appeared in Phil. Trans. R. Soc. Lond. 7 (1672) 4032, Issue 82, dated 22 April 1672.
20. Newton (1704) I, 76.
21. Idem.
22. See for example King (1955), 74.
23. Turnbull (1959), 3: letter of Newton to an unknown correspondent, 23 February 1668/9.
24. Ibid, 96: letter of Newton to Oldenburg, 6 February 1671/2.
25. Ibid, 84: letter of Newton to Oldenburg, 29 January 1671/2.
26. See above, ref (24).
27. Had the instrument been kept latterly by Wickins it would presumably have been accessible to Newton at least until Wickins left Cambridge in 1684 to take up the living at Stoke Edith near Monmouth: however, the fact that Newton and Wickins ceased sharing rooms in 1673 suggests that it remained with Newton. More (1934) 124.
28. Newton (1704), 'Advertisement' on $\pi 2$.
29. See Cohen (1974), 89 n88, 98. The foliation within U.L.C. MS Add 3970 is given by Whiteside (1969), 552 n9.

30. Shapiro (1980), 230.

31. Ibid, 233 and n61.

32. Turnbull (1961), 338: translation of memoranda by Gregory, 5, 6 & 7 May 1694. Shapiro (1980), 212 n5.

33. There is no satisfactory date for the Fundamentum opticae. Shapiro dates the composition of the Opticks to "the years surrounding 1690" (idem), and Whiteside (1969), 522 n9, to a "few years" after 1685.

34. Professor H. Guerlac has not found the discussion of telescopes in this proposition and the following one contained in any of the various drafts, except for the manuscript used by the printer of the 1704 edition: personal communication, 13 Sept. 1980.

35. It has not proved possible to check independently the date of the quick-silvered glass telescope mirror made "five or six Years ago", i.e. about 1682 (p77). The discussion of Edmond Halley's observations from his diving bell (p139) was added at a later stage since these experiments were begun in 1689 but principally carried out in 1691: Ronan (1970), 102.

36. Turnbull (1961), 355.

37. Turnbull (1959), 84: letter of Newton to Oldenburg, 29 January 1671/2.

3.6 PROVENANCE OF THE NEWTON TELESCOPES

3.6a The Heath and Wing Telescope

Although Newton's small reflecting telescopes were not the earliest to have been made, nor necessarily the most successful of the 17th century instruments, they were certainly the most significant, and their influence was felt well into the 18th century.

They had been the means of introducing Newton to the Royal Society, and had led directly to the debate into the nature of light and colour which has been shown to have been an important influence on the development of Newton's optical concepts.(1) His account of the factors that brought him to construct the telescopes undoubtedly led to an acceptance of the constancy of dispersive power which had the important but unfortunate result of delaying the introduction of achromatic optics.

The reflecting telescope remained little more than a curiosity until the early 18th century, but Newton's description of his instruments and methods in the Opticks, published in a number of editions from 1704, brought the reflector to wider attention, and gave it a prominence that it had not previously enjoyed. It was this that stimulated Hadley's work, which in turn led to a period of active experimental work and to the firm establishment of the reflector, epitomised by the significant role it played in Robert Smith's influential Compleat System of Opticks of 1738. These developments will be discussed in a subsequent section.

If the early Newton reflectors were such a formative influence on the course of applied optics and scientific instrumentation, then the telescopes themselves (if they survived) would be items of considerable historical importance, and they would be expected to provide valuable material evidence for Newton's optical activities to supplement and test evidence from documentary sources.

A telescope which is normally represented as being the first made by Newton is reverently preserved in the collection of the Royal Society of London. Although it enjoys considerable exposure both as the most significant example of the great man's work in practical optics and as an important survival for the history of science, its claim to fame has never been satisfactorily investigated. This is particularly unfortunate since it has not been Newton's telescopes themselves that have influenced later workers, but rather Newton's description and recollections of his processes and instruments, particularly as published in the Opticks: the authentication of surviving apparatus would then be a necessary early step in evaluating Newton's accounts.

Some effort has therefore been made to trace the provenance or ownership history of Newton's telescopes and to check the claims made for the existing Royal Society instrument. While this was being done the opportunity arose for collaboration with A.A. Mills and P.J. Turvey, who were also interested in the Royal Society telescope and who have published a detailed physical examination of components of the instrument.(2) Although their conclusions are somewhat different from those presented here, their study is a useful example of the way in which the examination of scientific artifacts may provide evidence of value to the historian, a theme recently explored by R.G.W. Anderson.(3) The conclusions suggested by Mills and Turvey are more definite than the evidence appears to warrant, and it must remain an open question as to whether the Royal Society instrument can confidently be associated with Newton.

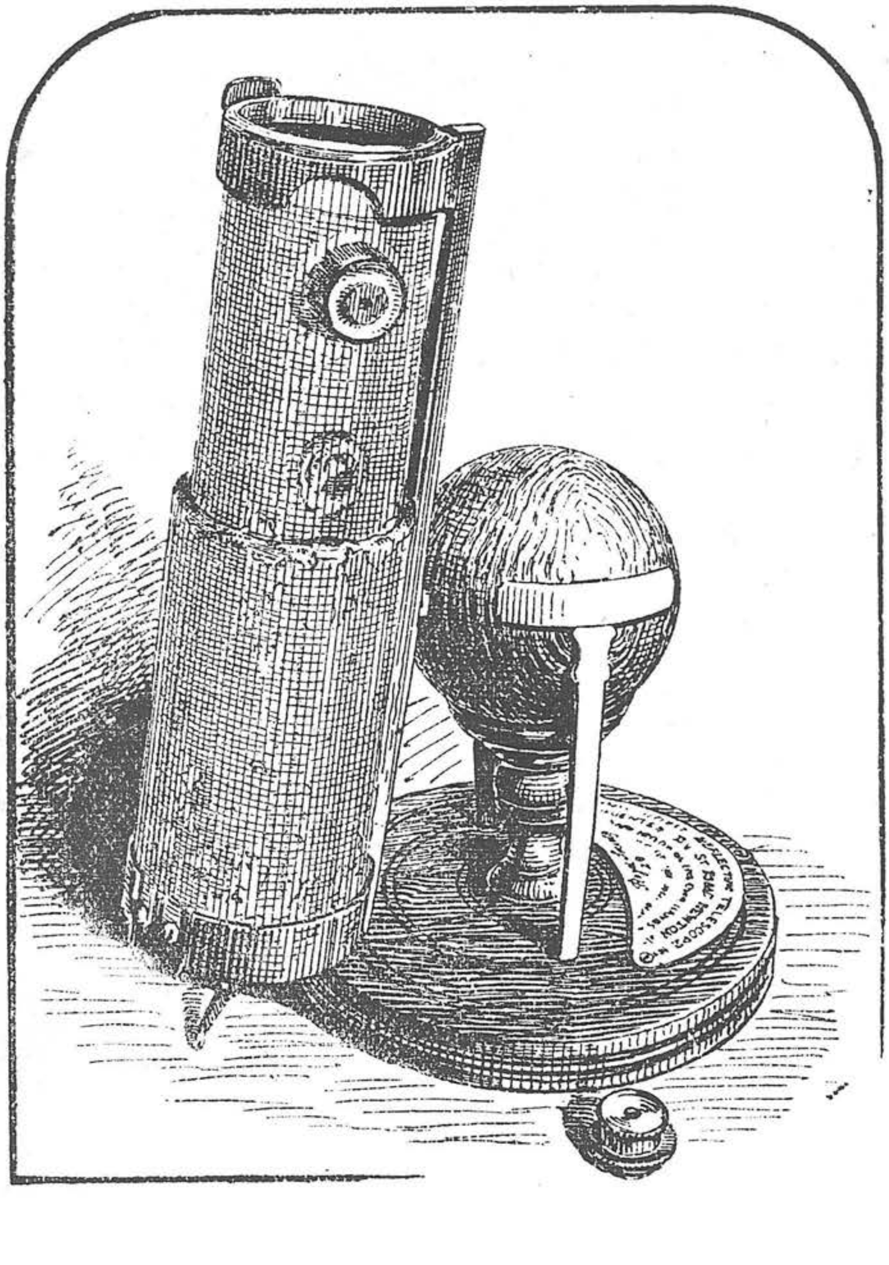

Fig. 3. The reflecting telescope attributed to Isaac Newton currently in the possession of the Royal Society of London, as depicted in the Society's <u>Record</u> for 1897.

The surviving telescope is externally very similar to Newton's second telescope, known from Oldenburg's drawing. The barrel is formed from two short paste-board tubes covered in light coloured vellum and painted black inside. The smaller diameter tube holds the inclined flat mirror and eyepiece, the larger diameter tube within which it slides having the mirror cell at its lower end. The cell is in two parts, both finely turned in wood and of a slightly smaller diameter than the 66mm external diameter of the tube. A stepped ring is glued into the end of the tube and has a flange within the tube against which the front of the main mirror is located. The mirror is held in place from behind by a threaded end cap, with a hollowed inner surface, which screws into the ring. The mirror itself is a very tight fit in the cell, presumably because the wood has shrunk, and is deeply tarnished except for a relatively bright outer ring where the surface has been in contact with the retaining flange. The maximum diameter of the mirror is 54mm ($2\frac{1}{8}$"), stopped down by the flange to 49mm: the rear surface is rounded at the edge and slightly convex, and the overall thickness is about 6mm ($\frac{1}{4}$"). Despite the very poor condition of the mirror surface, the focal length was obtained using direct imaging to determine the position of the centre of curvature and was found to be 206 ± 3mm (8.10" ± 0.15").[4]

The oval flat secondary mirror is crudely held by a single screw in its rear surface to an inclined support bracket, which is mounted on a split ring fitted into the upper end of the inner tube. A guide piece at the gap in the ring prevents the ring from being rotated in the tube, and so preserves the orientation to the eyepiece. The 'eyepiece' is however merely a turned wooden blank with no optics. It screws into a wooden mount set in the tube at the correct distance for a mirror of just over 8" focal length if the inner tube is withdrawn just so far as to expose an ink line inscribed round the tube. A small disc of cork has been used to fill a 13mm diameter hole which may have been the site of another eyepiece, and is correctly positioned for use with a 150mm ($6\frac{1}{8}$") focal length speculum if the tubes are again adjusted to the ink line.(5)

As with the second telescope, the Royal Society instrument is supported on an iron limb set on a primitive but effective ball-and-socket joint on a circular wooden base. The telescope tube is clamped at its ends by two brass bands, one riveted on the limb, and the other connected to the limb through a focusing screw beneath the mirror cell. The bands are however split, and are held closed by clips which can act together as a sighting mechanism for the telescope. The upper band has a semicircular cut-out matching the eyepiece mount diameter, and is just sufficient to allow the telescope (with the tubes set at the ink line) to be removed from its mounting when the clips are released.

The whole instrument is contained in an octagonal glazed case, and attached to the base of this are a brass mounted eyepiece, which will screw into the eyepiece mount but is clearly of a later date, and also an additional primary speculum. This second speculum has a less tarnished surface and evidence of a casting sprue on the reverse, and Mills and Turvey have measured its focal length as 7.52" (190mm).(6) Its large diameter of 59mm ($2\frac{1}{3}$") means that it cannot be fitted into the mirror cell, and so cannot be considered as a spare for the instrument as it stands. Rather, it appears to be an accretion which may have no relationship with this telescope or with Newton.

An engraved brass plate on the telescope base gives the attribution:

"THE FIRST REFLECTING TELLESCOPE/INUENTED BI S^{R}. ISAAC NEWTON/AND MADE WITH HIS OWN HANDS/IN THE YEAR 1671". The plate also bears the identification "Royal Society /28" which relates to the cataloguing of the Society's apparatus in the 1830s.(7) It is quite clear from such catalogues that this is the instrument presented to the Society on 6 February 1766(8), the gift being recorded in the Society's minutes in the following terms:

> "George Scott Esq^{r}. F.R.S., presented in the Name of Mess^{rs}. Heath and Wring, of the Strand, Instrument makers, a reflecting Telescope formerly belonging to Sir Isaac Newton P.R.S., and made by himself; for which Thanks were returned to Mr. Scott, and ordered to Messrs Heath & Wring." (9)

The telescope now exhibits clear signs of some alteration or rebuilding. The most obvious feature is the crudely blanked off hole in the tube. This, taken with the ink line on the inner tube, appears to indicate that the tube originally had a speculum of the length known to have been used initially by Newton, and that a larger focal length objective has subsequently been fitted. The high quality of the turning of the mirror cell and the fine screw thread of its components are compatible with mid 18th-century London workmanship, but they are not considered to be compatible with provincial production around 1670. The construction makes sophisticated use of the narrow gap between the mirror and the interior of the pasteboard tube, and this does not match our understanding of Newton's more humble intentions when constructing the early instruments. It has already been argued that the second telescope had a much simpler form of mirror support. Mills and Turvey also came to the conclusion that the mirror cell was made in the 18th century, based principally on the fineness and regularity of the screw thread.(10) The eyepiece mount and blank 'eyepiece' also appear to be of 18th-century origin: Mills and Turvey have demonstrated that the thread of the late eyepiece is not quite compatible with that of the mount, and therefore we must conclude that this is an accretion to the instrument.[11]

It is of course not certain that the instrument was altered before it was acquired by the Royal Society, and we may only be able to say that the surviving instrument is based on the telescope presented in 1766. It was certainly in its present form by 1831 when it was depicted in a reliable engraving[12], but no earlier illustration has been found. However, we may probably take the date back to 1806, and thus away from the period around 1830 when the Society's apparatus was being re-organised, by noting that Edmond Turnor described the telescope then at the Royal Society as having on it the inscription "Invented by Sir Isaac Newton, and made with his own hands, 1671".[13] This appears to refer to the same engraved plate, which would presumably have been added after any restoration work.

Thomas Heath (fl. 1712 - d. 1773) was one of the principal scientific instrument makers of the first half of the 18th century.[14] He was a respected and influential figure and was active in the Grocers' Company, which was one of a number of London Guild Companies to which instrument makers belonged; he served on several occasions as Warden and ultimately as Master of the Company. His substantial business was particularly known for the excellence of his surveying instruments, but a very wide variety of apparatus, some of it probably bought in from other makers, was offered at Heath's shop in the Strand. Among Heath's apprentices were George Adams I and John Troughton I, both of whom founded dynastic workshops that came to dominate the instrument market. Tycho Wing (1726-1776) was a surveyor who was apprenticed to Heath in 1741, and married his daughter. He was in partnership with Heath from at least 1758 (and possibly by 1750) until Heath's death in 1773.

The apparently reasonable assumption has been made[15] that the telescope presented in 1766 is that which Edmund Stone (1700-68; F.R.S. 1725) described in 1758 as having been in the care of Thomas Heath:

> "He [Newton] made two small ones, with an Object metal spherically concave, the second being better than the other; the worst of which he describes in the Philosophical Transactions, (at Numb. 80) and the other he sent to the Royal Society. The worst was not long ago to be seen at Mr Heath's, the Mathematical Instrument Maker in the Strand, having upon it, wrote with his own Hand, Isaac Newton." (16)

However, the only observation that Stone provided about the instrument was that it bore Newton's signature, and this is not present on the Royal Society instrument. Although Stone's reliability on factual matters has been criticised[17], it seems likely he would have been correct about the presence of a signature. The implication is then either that these are two unrelated instruments, or that the telescope was extensively modified after it was displayed by Heath. A further possibility which should perhaps be raised is that Stone may have intended the final sentence above to read "The worst was not long ago to be seen ..., having upon it, wrought with his own hand, Isaac Newton", the last seven words being a loose rendering of the inscription known to have been carried by the telescope at a later date. If this was the case then the instrument was probably presented in the same form as when Stone saw it.

Descriptions of the telescope now at the Royal Society are varied and confusing. Aside from incidental mention in popular or non historical works, it is occasionally represented as being the first instrument and dated 1668 or 1671.[18] Elsewhere it is normally described as being the second telescope, presented in 1671, and having remained in the Society's care.[19] The 1766 presentation of the surviving instrument is recorded in the various editions of the Record of the Royal Society[20] yet has been noted by only a handful of commentators, such as R.T. Gunther.[21] Perhaps the most confused account is that of R.A. Wells, who accepted without question that the surviving instrument was the second, but because he found that it did not correspond with the contemporary description by Oldenburg (in particular that the focal length was longer) he concluded that Oldenburg was describing the 1668 instrument.[22]

Stone's line of argument is that two instruments were made, and both are mentioned in Issue 80 of the Philosophical Transactions (p.3080). This is also his source for the statement that the second was the better of the two, and that this was sent to the Royal Society. It follows therefore that Heath must have had the first instrument. Gunther mixes up the two instruments by noting that it was the worst (and therefore presumably the first) that was with Heath, but confuses the reference with that for the description of the second instrument in Issue 81 (p.4004).[23] E.G.R. Taylor mistakenly supposed that both instruments were sent to the Royal Society and that the telescope described as being at Heath's shop had been discarded by the Society.[24]

A further area of confusion has been the additional eyepiece and speculum. The eyepiece can be fitted in a small retaining ring in the base of the telescope's display case, and it appears alongside the telescope in the engraved view in the 1897 edition of the Society's Record.[25] In 1842 Sir James South recalled that "many years back" the telescope had had an eyepiece which could not now be found, and furthermore he knew that the Assistant Secretary, J.D. Robertson, had made observations with the telescope which he could not have done without an eyepiece.[(26)] Robertson however reported that he had used "an eyepiece belonging to another instrument" and it may be this eyepiece that has remained associated with the instrument.[(27)] Robertson's predecessor James Hudson was able to satisfy the Council that he "never saw any eye-piece adapted for that instrument, or attached to it"; instead, he recollected that "the aperture was closed by means of a black button-screw, which had the appearance of being the locum tenens of an eye-piece" and he suggested that a comparison be made with Oldenburg's original description.[(28)] The additional speculum is crudely located on the base of the telescope case by three modern wood-screws. It does not appear in the 1897 engraving, as did the eyepiece, and so its association with the telescope may be recent. The heavily tarnished condition of the speculum fitted to the telescope has led some recent observers to believe that the mirror was not fitted but was the speculum alongside the telescope.[(29)] The separation of these two components from the telescope has even prompted H.C. King to claim that they are the original optical components, whereas the opposite is the case.[(30)]

Mills and Turvey have tested both the figure and the composition of the two primary specula.[(31)] Using a precision spherometer to measure the mounted mirror, they detected a small degree of astigmatism in the figure, which was ascribed to distortion from the contracting mirror cell. An optical test for the focal length of the less tarnished border zone, when compared with the spherometer results for the central zone, indicated that the mirror had a moderate turned-down edge. The brighter surface of the additional mirror enabled them to perform a Foucault test for the sphericity of the figure, and this, taken with the spherometer results, again indicated a turned-down edge. The chemical compositions of the specula were obtained by abrading minute samples from the rear surfaces of the mirrors with diamond tipped styli and testing these with an electron microprobe.(32) The semi-quantitative analysis gave the composition of the mounted speculum as copper, tin and arsenic in the ratio 6:2:1. For the additional speculum the ratio of copper to tin was 2:1, and 2 or 3% antimony was present also. The secondary mirror had major amounts of copper and tin present, but their ratio could not be measured, together with 20% antimony and 5% silver. Mills and Turvey concluded that the composition of the mounted speculum was compatible with a ternary alloy proposed by Newton, but was not the mirror of the second telescope, which was known to have contained silver. The additional speculum was of a binary alloy and therefore presumed to be of later workmanship. Newton's proposals for speculum alloys will be discussed in a later section.

Notes and References

1. Kuhn (1958).
2. Mills & Turvey (1979).
3. Anderson (1979).
4. Mills & Turvey (1979), 144, obtained a mean focal length of 8.20" by direct measurement with a spherometer.
5. Assuming a 1/6" focal length eyelens flush with the tube surface.
6. Mills & Turvey (1979), 145.
7. This engraving is inverted and therefore thought to have been added at a later date.
8. In particular Instruments and Apparatus belonging to the Royal Society (London 1834).
9. Roy. Soc. MS Journal Book, meeting of 6 February 1766. The intermediary was George Scott (1720?-1780; F.R.S. 1748).
10. Mills & Turvey (1979), 150 and plate 18. The threads were examined by latex casting and then use of a standard type of engineering profile projector. The test may turn out to be valuable in assessing instrument threads, but interpretation is likely to be hampered by lack of adequate control samples and insufficient knowledge of early machining techniques and out-working practice. A comparison with late 17th century wood threads attributable to Jack Dunning's workshop would be of interest in assessing the Royal Society's instrument. Mills and Turvey also point to the unlikely availability of hardwoods to Newton in Cambridge; however this seems an unreliable criterion.
11. Ibid, 148-150.
12. Brewster (1831), 80 figure 3.

13. Turnor (1806), 181 note. This was repeated in 1822 in Nichols (1817-31) IV, 19 note.
14. These notes on Heath and Wing are taken from Brown (1979); see also Taylor (1966).
15. Mills & Turvey (1979), 142.
16. Stone (1758), 298. King (1955), 74, mistakenly ascribes this observation to 1723.
17. Rigaud (1833-4), 659.
18. For example, the Science Museum label their modern replica of the Royal Society instrument as being of the 1668 telescope.
19. Thus, for example: Brewster (1855) I, 47; King (1955), 74; Thoday (1971), item 2; and Whiteside (1969), 439 n23.
20. Royal Society Record (1897), 171, and subsequent editions in 1901, 1912 and 1940. The 1897 wording is taken directly from the 1834 instrument catalogue entry: "Original Reflecting Telescope ...". By 1940 the wording has been made specific: "The Original Reflecting Telescope ...".
21. Both Gunther (1923), 316, and Wynter & Turner (1975), 194, record details of the presentation and give the instrument's date as 1671. Turnbull (1960), 13 n9 and 544, describes the telescope as a "model of Newton's reflector" received in 1766. The presentation is discussed in Mills & Turvey (1979).
22. Wells (1971), 343.
23. Gunther (1923), 317.
24. Taylor (1966), 25, 138.
25. Royal Society Record (1897), 172: reproduced here as Fig. 3, p.151.
26. Roy. Soc. MS MC.3.226: letter of Lubbock to Northampton, 8 June 1842.

27. Royal Society Council Record 1 (1832-46) 387, meeting of 9 June 1842.

28. Roy. Soc. MS MC.3.227: letter of Hudson to Robertson, 11 June 1842.

29. Thus, for example, Wells described the speculum as $2\frac{3}{8}$" diameter, which refers to the additional speculum and not the mounted one: Wells (1971), 342.

30. King (1955), 73.

31. Mills & Turvey (1979), 144-7.

32. The technique is described in Mills & Wilson (1978) where a semi-quantitative analysis is given of the mounted speculum, identified merely as a "speculum from an early telescope."

3.6b The Royal Society's Repository

The telescope which Newton had passed into the care of the Royal Society in 1671 was kept in the Society's Repository or Museum, which housed its extensive collection of natural and artificial (or non naturally occuring) specimens. It is clear that conditions in the Repository were not always suited to the safety of the collections, and an analysis of the Society's records indicates that the telescope deteriorated and finally disappeared about the middle of the eighteenth century.

The Royal Society was founded in 1660 for "the promotion of Physico-Mathematicall Experimental Learning", and was awarded its charters by Charles II in the following years. The active nucleus of founder fellows had been in the habit of meeting together at Gresham College in the City of London, and it was at Gresham that the Society was principally based for its first fifty years.(1) Gresham College had been the home of the merchant Sir Thomas Gresham, who in his will had established it as a public college, with a lecturing staff of seven salaried professors. Initially the Society met in the rooms of those professors who were fellows, but by early 1661 it acquired a room of its own for meetings and for conducting experimental work. By 1665 its premises had been expanded to include

> "one publick Room to meet in, another for a repository to keep their Instruments, Books, Rarities, Papers, and whatever else belongs to them: making use besides, by permission of several of the other Lodgings, as their occasions do require". (2)

Over succeeding years as the Society's accommodation needs developed it was able to acquire additional unwanted space from the Gresham trustees and from individual professors, until its offices, library and repository eventually occupied a considerable proportion of the

College building.(3)

The Society's practical experimentation was placed on a regular footing in 1662 when Robert Hooke, arguably the most dynamic and influential figure in the Society's early years, was appointed as 'Curator of Experiments' and responsible for providing an unflagging stream of original demonstrations for the weekly meetings. Hooke, who from 1664 was resident at Gresham as professor of geometry, was also made Keeper of the Repository and was closely involved with the collections over the period of their most rapid expansion.(4)

The first attempt to regularise and systematise the Society's burgeoning collections seems to have been made by Nehemiah Grew, physician and plant anatomist, and at the time also second Secretary to the Society, who was asked by the Council in 1678 "at his leasure, to Make a Catalogue and Description of the Rarities belonging to this Society".(5) The result of his labours was published in 1681 as the Museum Regalis Societatis, a detailed description and discussion in nearly 500 folio pages of the whole range of the Society's collections, reflecting nonetheless his clear inclination for the natural curiosities. The instruments and models are grouped with coins and antiquities in Part IV under the heading "Of Artificial Matters" and the description of the telescope is tantalizingly uninformative, the reader being referred for all detail to the account in the Philosophical Transactions for 1672.(6)

The impetus for his work may have been a general concern felt by the Council for the security of the various collections following the removal of the Society's library to Gresham from Arundel House before the demolition of the latter in 1678. The catalogue of the library produced at the time for the Council was compiled by

Michael Weeks, the Clerk, and Henry Hunt, the Society's 'Operator', and it seems most likely that Hunt was closely involved with the preparation of Grew's catalogue also.(7)

Grew succeeded Hooke as Curator of the Repository in 1682, and when in 1696 the Council decided at last to appoint a full-time servant to look after the collections they turned to Henry Hunt, making him first Keeper of the Library and then both Keeper of the Repository and Housekeeper.(8) Hunt had entered the Society's service in 1673 as Hooke's boy assistant, and in 1676 he had succeeded Richard Shortgrave as Operator, responsible for preparing and performing Hooke's demonstration experiments.

Henry Hunt remained as general factotum to the Society until his death in 1713, two years after the Society had moved its being (and all its possessions) from Gresham to Crane Court off Fleet Street. Although his work and loyalty were highly esteemed, and although the Fellows in general, and Hooke in particular, had a warm regard for him, yet there is no doubt that during the time that he was responsible for the Repository the collections appear to have slipped into disorder. Perhaps the fact that on several occasions he was able to lend the Society money in a period when its finances were in considerable difficulties may have helped the Council to overlook these shortcomings.(9)

An early indication of the worsening state of the Repository is contained in the diary of Frans Burman, the Dutch theologian, who visited Gresham College in 1702, commenting that:

> "One room was full of rare instruments collected from all parts of the world of which an english description [by Grew] has been published in folio. Here were many magnets, one of prodigious size, at least a foot, but not formed in iron nor suspended, but carelessly thrown amongst many of different size." (10)

Much more forthright criticism was made in 1710 by the German literary connoisseur and traveller Zacharias Conrad von Uffenbach, whose diary paints a picture of woeful neglect at Gresham:

> "Both in Germany and elsewhere an exalted idea of this Society has been formed, both of it and of the collections they have in their Museum, especially when one looks at the Transactions of their Society and the fine description of the Museum by Grew. Thus foreigners have just grounds for amazement when they hear how wretchedly all is now ordered. But it is the sight of the Museum that is most astonishing. It consists of what appear to be two long narrow chambers, where lie the finest instruments and other articles (which Grew describes), not only in no sort of order or tidiness but covered with dust, filth and coal-smoke, and many of them broken and utterly ruined. If one enquires after anything, the operator [Henry Hunt] who shows strangers round ... will usually say: "A rogue had it stolen away", or he will show you pieces of it, saying: "It is corrupted or broken"; and such is the care they take of things! Hardly a thing is to be recognised, so wretched do they all look." (11)

The Operator was permitted by the Council to charge visitors to let them see the Repository in order to augment his salary, but Uffenbach was in no doubt that exposing such collections to the idle curiosity of the public placed them at risk, a view he expressed more clearly after his visit to the more frequented Ashmolean Museum in Oxford:

> "The things in the museum ... are in better order than those at Gresham. The wonder is, that they are as well preserved as they are, as every one, in true english fashion, handles them roughly, and all persons (even women) are admitted on payment of 6d, who run about, lay hold of every thing, and will not be hindered by the sub-custos." (12)

The travel guide used by Uffenbach while he was in London was the then recently published <u>New View of London</u>, attributed to Edward Hatton. This includes an extended account of the Royal Society's museum, in which Hatton described over 300 of "the most remarkable Rarities in the Repository at Gresham College, mostly abstracted from the Learned Dr Grews Account, and the rest as I find them in the Repository."(13) The items are listed in the order given by Grew (with the additions placed at the end) and their descriptions are clearly based on Grew's. The particular items selected may be compared with those known to have survived in the Repository twenty years later, from which it would seem that Hatton examined these items and described only those that he saw. Thus we can deduce that the Newton reflecting telescope was still present and recognisable in 1708.

Very soon the collections were to be subject to the upheaval of being packed and moved to new premises.(14) For a number of years the Gresham trustees had been attempting to secure an Act of Parliament to enable them to rebuild the College on a smaller scale in order to relieve themselves of what was becoming an increasingly difficult financial burden, and inevitably this meant the exclusion of the Royal Society.(15) The fifty year long association between the College and the Society, which had been to the great mutual benefit of both but had become soured by the stance of the Gresham trustees, was brought to an end in late 1710. At Newton's instigation the Council acquired two houses in Crane Court off Fleet Street "being in the middle of the Town out of noise, and ... a proper place to be purchased by the Society for their meetings."(16)

It was soon clear that the museum collection could not be accommodated within the house, and so a new Repository building was constructed at the rear of the house, apparently to a design by Sir Christopher Wren.(17) The collections were brought from Gresham "with what convenient Speed" Henry Hunt could muster, but they had to wait at Crane Court for ten months until the new building was at last ready and a committee could be charged "to take care of the due placing of the Curiosities in the New Repository".(18)

The small reflecting telescope appears to have survived the move to Crane Court and was subsequently mentioned by Newton's antiquarian chronicler William Stukeley in a manner that suggests that he had seen the instrument. Stukeley was first introduced to the Royal Society, and to Newton, in 1718 when he took up medical practice in London. The friendship that developed between them in the closing years of Newton's life led Stukeley to begin collecting reminiscences of Newton in 1726 for a biography, and in a short manuscript account of Newton's life he noted that he had

> "made that famous reflecting telescope now in the Repository of the Royal Society, and likewise [in 1704] that concave Speculum, or burning glass ..., now in the same repository." (19)

More problematic is the reference by Count Francesco Algarotti recently cited by A.A. Mills and P.J. Turvey(20), since the telescope that Algarotti describes as being Newton's first must have been seen by him after the Royal Society instrument had substantially deteriorated as will be discussed later. Algarotti was a Venetian nobleman who visited England in 1736, and again in 1737-8, being sponsored as a Fellow of the Royal Society by Martin Folkes in 1736. He produced a popularising text on Newtonian philosophy Il Newtonianismo per le dame (Naples, 1737) which took the form of six dialogues principally about the nature of light and colour, and which passed through several editions. Having explained the nature of aberrations affecting refracting objectives, he described Newton's invention of a reflecting telescope, adding (in the English translation of 1739):

> "I have myself seen the first telescope of this sort, worked by those hands [Newton's] which had pointed the planets to their road ... This instrument is preserved in a city of England, where philosophy and politeness hold a mutual empire; with this are treasured up those prisms which the first time differently refracted the rays of light in the hands of our great philosopher ..." (21)

It will be argued later that this cannot refer to the instrument in the Royal Society, but may describe material at Trinity College, Cambridge, unconnected with Newton.

Henry Hunt died very shortly after the Society's move to Crane Court, and he was succeeded as Housekeeper and Keeper of the Repository and Library by Alban Thomas, who was at the same time appointed Clerk (or Assistant Secretary).[22] Although this was a temporary arrangement, the posts were to remain linked.

Thomas departed abruptly ten years later, leaving suspicions of Jacobite involvement and also outstanding debts that the Society may never have recovered. His valuable cataloguing work in the Library was not matched in the Repository: a Council Committee charged with inspecting the state of the Library and Repository after his departure could only report that "we have been in the Repository, but as the Curiosities there are not numbered, and we find no Catalogue, we are not able to give any particular account of them."[23] By this time also another shortcoming of the Repository was being increasingly felt. The dampness, which had first been discussed by the Council in 1714, had by 1719 caused sufficient damage to specimens for the President to pass on to the Council "some Complaints made to him about the State of the Repository": the problem, however, had still to be solved fifteen years later.[24]

Alban Thomas's position was filled in 1723 by Francis Hauksbee, nephew of the notable Francis Hauksbee 'the Elder'.[25] Hauksbee senior had been a leading instrument maker and an experimenter of great skill. Under Newton's Presidency the practice of regular demonstrations at meetings had been revived, with Hauksbee acting as the Society's curator of experiments until his death in 1713, and his work proved an important influence on Newton.[26] Hauksbee junior was also an instrument maker and popular lecturer, and he operated from premises adjacent to the Royal Society in Crane Court. Although he did perform some experiments before the Society, he did not succeed to his uncle's post: ten years later however, on the recommendation of "divers Members of the Society", he secured Thomas's positions of Housekeeper, Clerk and Keeper of the collections, retaining these until his death in 1763.

At Hauksbee's election a point in his favour had been that he was already familiar with the museum collections, having "frequently been in the Society's Repository to look over the Raritys", and that he could offer £400 security for the collections in his care - a new requirement introduced by the Council only four years earlier. The committee set up immediately after Hauksbee's appointment to investigate the state of the Library and Repository presented a critical report indicating that Thomas had been lax not only in cataloguing but also in controlling loans, and the Council promptly raised poor Hauksbee's liability to £600.(27)

The state of the Repository however clearly continued to cause concern, and in 1729 the council decided to revive the 1723 Committee for inspecting the Society's Library and collections. Apparently this was at the suggestion of John Hadley(28), now Vice-President, but was presumably made with the strong support of the new President, Sir Hans Sloane, himself an inveterate collector, whose museum was on at least one occasion held up as an example to the Society.(29) The Committee on the Repository, in its several reports to the Council between 1729 and 1734, provided ample confirmation of Uffenbach's dispiriting comments on the condition of the collections twenty years earlier. Thus we learn in their initial report that they found the Repository "in great disorder", and when they began checking the animal specimens they discovered that "several of them cannot be found very many more are greatly Damaged, Some by time, others for want of Convenient Cases to preserve them in". Indeed it was clear that "the greatest part of the Repository will soon perish & become useless" unless the Council was prepared to take effective action.(30) In their summary report came the first admission that material might have been stolen:

> " ... it is scarcely to be expressed the confusion and disorder they [the Committee] found everything in: the greater part of what was expected to be there being lost or imbezzled, and most of what remained in such bad condition either thro' want of care or injury of time ..."

Thus, for example,

> "the Committee are Surprized to find so many curious Specimens of Oriental & other precious Stones in the Lists of Donations not to be found in the Repository notwithstanding their most diligent Search." (31)

Our concern here however is with the scientific apparatus of the Society. It was quickly apparent to the Committee that they were largely in a parlous state, and they somewhat tersely commented that "The Instruments and Models of Engines are generally so broke to pieces that few of them are worth preserving."(32)

Apart from the expected problems of dirt, dampness and decay, the collections now lacked even basic security. The Committee observed that, apart from the specimens having totally inadequate casing to protect them,

> "the Repository is always a common passage or thoroughfair to the family dwelling in the Society's House, and which is indeed a very great conveniency to that family, but is they think not quite so proper for the Repository to be thus exposed." (33)

The Committee's principal interest was in providing adequate accommodation for the natural history collections, and in stabilising decayed and damaged specimens. By the time the Committee was dissolved in late 1733 a physical examination of all the surviving specimens had been completed, and its work was continued alone by Dr Cromwell Mortimer, Secretary of the Society from 1730 to 1752, who was a close associate of Sir Hans Sloane and had acted as the Committee's secretary. Mortimer was also entrusted with the more weighty task of compiling a detailed catalogue of the collections along the lines of Nehemiah Grew's earlier work, and this occupied him until at least 1736.(34) During this time extensive alterations were made to improve the state of affairs in the Repository: the flooring was inspected, the walls lined with deal, and new locking cases were installed. Proposals for creating new windows and a passageway to separate the Society's tenants from the collections may however not have been carried out.

Minutes of the Repository Committee from 1730 to 1733 survive as do three manuscript inventories of this period(35), allowing the Committee's work to be at least partly reconstructed. Since these shed light on the fate of the reflecting telescope presented by Newton they will be examined in some detail. The Committee's cataloguing work appears to fall into three stages. Firstly they made a preliminary examination of all that survived, completing this in September 1731, in the course of which they undertook the more urgent repair work. Then, between March and October 1733 they reviewed the collections and numbered such material as was thought worthy of preservation, or at least of further consideration. Finally Mortimer was to produce a descriptive catalogue along the general lines of Grew's, but this last stage may not have been completed and the catalogue itself is not known to survive.

The Committee began their work in 1729 by comparing the specimens with the only available catalogues, namely a copy of Grew's work in which someone had begun to number the items in the margins, and a manuscript catalogue "Supposed to be drawn up by a Servant of the Clerk for his private uses" in which rather more of the items were numbered and which included additions to the earlier catalogue.(36)

At their regular weekly meetings the Committee worked systematically through the collections, following Grew's classification scheme, and identifying what they could. Minutes for their meetings are only available from January 1730 when they had advanced so far as to be examining the fish. It is clear from a comparison of the items described in the first few minuted meetings with the annotations made in the Royal Society's existing manuscript Catalogue A (MS 413) that it was this catalogue that was the principal inventory being used by the Committee, and it may be dated at about 1720.(37) Although the Committee began by noting which items were missing they soon turned to listing only those that survived, presumably because the survival rate was found to be increasingly poor in the vegetable and mineral sections and the items more difficult to identify.

By the time they reached the models and instruments in July 1731 the old manuscript catalogue had ceased to be of any practical use. The original compiler of this had begun a classification for 'artificial matters and antiquities' that was a little different from Grew's, but had clearly lost interest before he had inserted more than a handful of the items noted by Grew.

The 'ruinous' condition of the instruments, models and engines meant that "most [could] not be distinguished", and it was decided that those that could not be recognised should "be laid aside & kept for some other ex-amination."[38] In four meetings 118 artificial curiosities (as well as antiquities and coins, which were treated separately) were listed and numbered. Several of these were comparatively insignificant, and those that could not be positively identified were carefully described, suggesting that the Committee had been cautious in what they decided to lay aside. In spite of this, the Newton telescope is conspicuous by its absence, but instead we find that amongst the first instruments examined were "the 2 Specula of S^r^ Isaac Newtons reflecting Telescope".[39]

By mid September the Committee were able to announce that they had "gone thro' the Museum for the first time"[40] but the projected second review of the Repository had to wait for the fitting of further storage cupboards and for the preparation of a reliable list of donations of objects. The labour of compiling this list, which is the existing Royal Society manuscript Catalogue D (MS 416), was divided between several Fellows who scanned the minute books of the Society's meetings between particular dates, entering donations under 19 different subject headings.[41]

The Committee resumed their meetings in March 1733, working this time from a revised catalogue drawn up by Cromwell Mortimer and combining Grew's catalogue and the newly prepared donation list. This is the Royal Society's manuscript Catalogue B (MS 414), which was called for, section by section, by the Committee and which is classified by a new scheme of Mortimer's devising similar to that used by Grew.[42] This catalogue is thus only a list of the items that the Committee might hope to find in the Society's care, but it has the advantage over MS 413 of being an exhaustive listing, and of being annotated throughout to indicate which items survived. Meeting twice a week, the Committee sorted and re-numbered the material in each section of the catalogue, identifying each item with the relevant catalogue entry, against which the item's number was written in pencil. Occasionally they paused to examine "severall articles wch had been overlooked & inserted them in their pro[per] places", and one may detect a sense of relief when in October 1733 they numbered the final artificial curiosity "with wch they ended their review of all ye curiosities found in ye Repository".(43) Again, the 1671 Newton telescope has no mark against it, indicating that it was not in the Repository, but we find an entry for number 180 "The 2 Specula for S^{r} Is. Newton's reflecting Telescope".(44)

Evidence of this sort however poses problems of interpretation. For example, although we can be reasonably sure that the telescope was not in the Repository, could it have been elsewhere on the Society's premises? In June 1728 James Bradley, Savilian Professor of Astronomy at Oxford, returned a large objective lens which had been presented to the Society in 1691 by Huygens but had been on loan to various Fellows since 1713.(45) Almost immediately the Council decided that this lens, together with the two other long focus lenses by Huygens and a collection of historic microscopes bequeathed by Leeuwenhoek in 1723, should be "reposited under a New Lock in the Closet in the Council Room".(46) As a result none of these items is recorded in the inventory as being present in the Repository in 1733.(47) It does not appear that instruments were kept in the Council Room before this time or that any were added subsequently, so that we may tentatively conclude that by 1731 the Newton telescope had either left the Society or was survived only by parts.

Similarly it is not possible to identify firmly the 'two specula' as being from the Newton telescope, although this seems very likely. The Society does not seem to have retained the mirror of the 4 foot instrument begun by Cox and which will be described later, and one would in any case expect comment on the large size of this mirror. No other reflectors are mentioned by Grew, and although it is remotely possible that early mirrors by Hooke might have survived there is no clear reason why Hooke would have kept such items in the Repository. The mirrors cannot have been from the Society's Newtonian telescope by John Hadley, since this was still on loan to James Bradley at Wanstead. They might perhaps be mirrors for a Newtonian produced after Hadley's, although they would then have been comparatively modern. However, this subsequent work appears to have been conducted away from the Royal Society, and it seems a little unlikely that parts would have found their way into the Society's Repository: certainly none are recorded amongst the donations. The term 'Newtonian' for a reflector employing Newton's optical system was certainly in widespread use by 1735[(48)], and was probably well enough known to have been used by the 1731 Repository Committee: yet the mirrors are specifically described as being for Sir Isaac Newton's telescope rather than for a Newtonian telescope. It would appear then that the mirrors were appreciated as being of some antiquity, and that they were assumed to have been associated with Newton himself; however a number of other possibilities exist which cannot be definitely excluded.

The Committee's concern not to destroy material unnecessarily is seen in their treatment of badly damaged material from the animal collections, many items being placed on one side for yet another review, the Committee "not esteeming themselves duly authorised to deny them a place in the Repository".(49) The Council subsequently ordered that "the imperfect models of machines, & other works be laid aside in some waste Room or Garret till the review of the Repository be compleated".(50) One may speculate that parts of the Newton telescope went unrecognised with this discarded material, or that the tube and mounting had been damaged and were simply not felt worth retaining: the optical components would be seen as the important parts and these were being preserved. The fate of this material is not known, but it may well ultimately have been thrown away, as were those natural history specimens which had been found to be "entirely useless and spoil'd".

By early 1736 a considerable portion of the catalogue had been completed by Mortimer, and John Hadley was able to praise "the Good State and Condition wherein the Repository is at length brought, by the great care and Application of the Gentlemen of the Committee".(51) In September 1737 Hauksbee was being asked by the Council to call in the instruments which had been borrowed but not returned.(52) A year later it was agreed by the Council that Mortimer and some colleagues were to draw up an inventory and identify the items in Hauksbee's presence so that Hauksbee could then "sign the Inventory, and take upon himself the charge of the things therein contained".(53)

One is left with the clear impression from the minutes of the Society's Council that, through the efforts of Mortimer and others, the Repository had been well ordered and the safety of its contents assured. An indication that this was not so was noted very shortly after Mortimer's death by William Stukeley in his diary for 1752:

> "Further he [E.M. da Costa] represented that foreigners of curiosity, as well as our own peoples, often desired to see our museum, which had formerly a reputation both at home and abroad. He was ashamed to recite what a ruinous forlorn condition it was now in, and prayed it might be amended". (54)

Emanuel Mendes da Costa (1717-1791) was one of the more colourful members of the London scientific community at the middle of the century and his brief but scandalous association with the Royal Society has recently been explored by P.J.P. Whitehead.(55) Da Costa apparently made an early mark for himself, for in 1747 he was elected Fellow of the Royal Society, being sponsored by, amongst others, the President of the Society, Martin Folkes. His proposal had cited his particular knowledge of "the Mineral and Fossil parts of the Creation", and it is the fields of mineralogy, palaeontology and conchology that he is principally known, both as a writer and as a collector. He formed a close friendship with William Stukeley who like Folkes was a leading member of the Society of Antiquaries, and in 1752 he became a Fellow of that society also.

Whitehead has shown that by the early 1760s da Costa was a much respected member of the antiquarian and scientific worlds, well integrated into the intellectual circles of his time.(56) He was therefore widely supported in his application to succeed Hauksbee to the responsible position of Clerk to the Royal Society, and on 3 April 1763 he was confirmed as Clerk, Librarian, Keeper of the Repository and Housekeeper.(57)

Da Costa's beloved library and natural history collection moved with him to the house provided for his family in the Royal Society's premises, and Whitehead has concluded that it was his reckless buying of books and specimens that led to his serious financial problems. His purchases had already outrun his resources in 1754 when he had been imprisoned for debt and his collections impounded, but his continuing difficulties now prompted embezzlement. As Clerk he assisted in the collection of membership fees and from soon after his appointment he was persuading new Fellows to pay a life fee but was only passing on the annual fee.

The Council did not have long to wait before recognising the error of their judgement. The affair was uncovered in mid 1767 and by June 1768 da Costa's collections at the Royal Society had been sold to help pay a debt that eventually totalled £1,500. Da Costa was sued by the Society for the remainder and imprisoned; and although he continued his scientific publishing from the King's Bench Prison and even gave successful subscription courses of lectures on fossils and shells, his connection with the Royal Society was now at an end.

His keen interest in the development of his own collections, and his activities as a dealer and intermediary between other natural history collectors, inevitably raises some doubts about his handling of the Royal Society's collection.(58) However, although there are some puzzling discrepancies between the inventories of the early 1730s and those of the 1760s, there is no clear evidence of da Costa removing material from the Repository or not acting according to the somewhat looser curatorial ethics of the day.

Two items of some historic interest which are relevant to this discussion do however seem to have disappeared about this time. One of these, "a Speculum given by Mr Newton", was a composite burning glass comprising seven circular mirrors each of about one foot diameter with which the Society's President provided some dramatic demonstrations in 1704. The device was well known from contemporary descriptions(59) and is the mirror mentioned by Stukeley. It seems surprising that such a relic of Newton should not have been preserved, yet it is not in the 1765 inventory.(60) The apparent absence of the second item, "a wooden model of Dr Hook's Reflecting Quadrant", from the later catalogue is all the more surprising because of renewed interest in the 1740s in the progenitors of Hadley's reflecting quadrant.(61)

The Council had taken the opportunity whilst selecting a successor for Hauksbee to define the duties of the Society's officers more clearly, stressing for example that the keeper of the Repository was to be diligent in keeping methodical catalogues.(62) Henry Baker, James Parsons and William Hudson were appointed Inspectors and on 26 May 1763 they "Began the Inspection and Regulation of the Repository".(63) The inventory of natural history specimens (MS 415) was completed in November 1763, and was followed two years later by an inventory of antiquities, models, instruments, curios, etc (MS 417) to complete the survey.(64) In their report to the Society the Inspectors claimed to have taken

> "an exact account of all the ... instruments of several kinds ... which belong to this Royal Society ... [which] will furnish a Compleat account of the whole Collection in your Repository. By these two inventories you will know what Treasure you are possessed of; you will know (which you have not done for many years) what is under the care of your Repository Keeper, and what he is Accountable for; the want of which your Inspectors Apprehended has occasioned the loss of numberless things of value ... Your whole Collection is now clean and disposed in such a Manner as to make an handsome Appearance, and every Article required after can be found with ease." (65)

At last, it would appear, everything was in good order and there were no 'loose ends', as there had been in 1733, in the form of unidentified and damaged specimens which could therefore not be included in the inventory. Detailed evidence for da Costa's work in the Repository is scant, but surviving accounts for his expenses provide a few clues.(66) There was a fairly high expenditure on boxes for specimens in 1764-6, and there was clearly considerable activity in the Repository in 1766 and 1767. If the damaged residue of the collections was indeed disposed of in some form of purge, then this may perhaps have happened in June 1764 when da Costa hired "a Man to remove the rarities".(67)

The 1765 catalogue (MS 417) again includes an entry for the two Newtonian telescope specula, now described as:

"76 "The Metals belonging to S^{r} Isaac Newton's Reflecting Telescope. a Smaller and larger"

There is no evidence to suggest that these are different from the two described in 1731(68) and so it will again be assumed that these are the surviving optics from the 1671 telescope by Newton.

The inventory was continued by the keeper of the Repository as a running catalogue for a number of years, the latest entry in this section being dated 1770. The donation in 1766 of a further telescope by Newton was recorded as:

"87 The original reflecting Telescope made by Sir Isaac Newton. presented by Mess.^{rs} Heith and Wing"

The Council was more fortunate in its choice of a successor to da Costa: John Robertson (FRS 1741) was appointed in January 1768 and gave exemplary service until his death in December 1777. He in turn was succeeded by his eldest son, also John Robertson, who however soon became lax and negligent in his duties, and resigned in January 1785 following frequent complaints and admonitions.(69) During his unsatisfactory period of office the Society moved its premises from Crane Court to a suite of rooms in the Government's new Somerset House. The Royal Society had by this time come to be regarded by Government as a national institution, being consulted frequently on scientific topics, and the Council had been pressing for assistance with accommodation to replace Crane Court, which was proving inadequate for the growing number of Fellows. The Government's offer to provide suitable rent-free rooms in Somerset House was not immediately accepted because the accommodation allocated was found to be too small. The Council's principal complaint to the architect was that there was "no room at all allowed to the Society's Museum", and although an alternative scheme for the use of the rooms was suggested(70) the Council decided in 1779 to accept the original offer, reducing their accommodation requirements by gifting their collection to the Trustees of the British Museum.(71) The Council's action was in effect an acknowledgement that their own museum had been eclipsed by that at Bloomsbury which now included the extensive collection acquired for the Nation from Sir Hans Sloane. The building of Somerset House moved apace and the Royal Society first met in their new rooms at the end of 1780. The houses in Crane Court were sold in 1782.

The scientific instruments were of continuing use to the Society and were not transferred to the British Museum with the other collections, but were taken to Somerset House, being described in a guide of 1806 as "a variety of apparatus and instruments".(72) It may be imagined that the upheaval of packing the Society's numerous and diverse possessions, and the division of both the Library and the Repository for dispatch to two separate locations, provided ample opportunity for small items to be lost or to lose their identity, particularly in the less than capable hands of John Robertson, junior.(73)

Thus it appears that in common with many other instruments and models in the Royal Society's Repository, the 1671 reflecting telescope became dilapidated during the first half of the eighteenth century, until eventually only its principal optical components were recorded. Conditions in the Repository were frequently at a low ebb, and the collections were in the care of curators who were overworked or negligent (and in one instance dishonest) in their duties. The instrument collection was finally put in good order only in the early nineteenth century.

The period of peace following the lengthy French wars at the beginning of the nineteenth century was one in which the Government turned increasingly to the Royal Society to resolve scientific problems of various types and to undertake investigations on its behalf. The long overdue reform of the system of weights and measures, and its establishment on a sound scientific basis, was referred to the Society in 1816. The work of Henry Kater that led to the introduction of the Imperial System in 1824 however was intimately connected with the parallel and pressing problem of developing the geodetic framework of the Government's Ordnance Survey and ultimately was to involve exacting measurements conducted across the globe. The Navy's growing hydrographic role, together with the call of national prestige, led to a series of expeditions, notably those in extreme latitudes aimed at discovering the North-West Passage. The Society was active in encouraging these, and through close collaboration with the Admiralty ensured that programmes of gravitational, magnetic and other observations were carried out.

The Society's collection of instruments, swollen by the apparatus used by Kater and others, now served two purposes. The Society held instruments that could be and were lent for scientific experiments and expeditions, and it also provided a secure repository for apparatus such as length standards that had to be regarded as reference pieces accessible only under controlled conditions. The collection of course still included an assortment of items (including the Newton telescope) that were now principally of historic interest, but even some of these, such as George Graham's standard yard, were becoming recognised as having important scientific reference value. These instruments were however not all kept in the Society's rooms. Geodetic instruments for a time remained with those of the Ordnance Survey, while further instruments were associated with the Board of Longitude with whom the Society shared a warehouse until the Board's dissolution in 1828.(74)

After the Society's principal collections had passed to the British Museum it is not clear whether there was adequate control over the instruments. Certainly this growing collection was not properly documented, as is made clear in a Council resolution of early 1827 that "As no accurate catalogue exists of the Instruments belonging to the Royal Society" a committee comprising Davies Gilbert as Treasurer, Captains Francis Beaufort and Henry Kater, and James South, the astronomer, was charged with drawing up an inventory.(75) In common with many other Fellows, South at the time was highly critical of many aspects of the Society's operation which were felt to be depressing its scientific prestige. A committee set up at his insistence recommended important reforms, but its report was later rejected.(76) Both Beaufort and Kater served with South on this committee and would have shared his views about regularising any shortcomings in the care of the instruments or their scientific availability: Beaufort was shortly to become Hydrographer to the Navy, and Kater had framed the Admiralty instructions for the care of instruments on the arctic expeditions.(77)

The 1827 inventory survives in two manuscript versions in the Royal Society's Archives: a principal copy(78), and a further copy with items listed by location.(79) As well as "Newton's Reflecting Telescope", also recorded at the same location was a "Concave Mirror apparently by Newton." It can be deduced that this was an objective mirror of about the same size as that in the telescope, and it is possible that this may be the slightly oversize mirror which is now associated with the telescope.(80) The catalogue was presented to the Council in April 1827, when they "Resolved that a Glass Case be made for Sir Isaac Newton's Telescope", which is the case in which the instrument is now displayed.(81)

In 1830 there was again considerable discontent amongst the scientific Fellows when it was learnt that Davies Gilbert, the interim President, had proposed the King's brother, the Duke of Sussex, to succeed him; but in spite of attempts to get John Herschel elected, Sussex won the contest.(82) Although his knowledge of science was slight, Sussex rapidly appreciated the need for a revision of the Society's policy and a thorough overhaul of its administration. During the first few years of his presidency, and with the active assistance of the new Treasurer, the astronomer John Lubbock, he reformed and regularised many of the administrative procedures.(83) Amongst the subjects to come under scrutiny was the security of the Society's various possessions. Apart from the apparent disarray of some sections, such as the papers and documents, there was the problem of exercising adequate control over borrowing by Fellows: comprehensive catalogues would have to be prepared and regulations for loans framed.

The informality of the existing arrangements is perhaps best illustrated by the disappearance in the period 1800-30 of the collection of historically important microscopes bequeathed to the Society in 1723 by Anton von Leeuwenhoek. The loss was pointed out in 1855 by the Council's most persistent critic of administrative shortcomings, Sir James South. The microscopes had apparently been lent informally to the surgeon and microscopist Sir Everard Home who had died in 1832, but enquiries by South and the Council failed to locate them.(84)

This problem was of course not a new one. Another often quoted example is the Tompion astronomical clock presented to the Society on John Flamsteed's death which was borrowed, probably by Sir James Lowther in the mid 18th century, and its connection with the Society soon forgotten: fortunately, it was ultimately acquired by the British Museum.(85)

The Council called for catalogues of the instruments, and of the Society's portraits, in March 1831.(86) James Hudson, the Assistant Secretary to whom the 1827 list had been entrusted, delivered a list of the instruments to the Council in June, and Henry Kater was asked to "revise this list, and make in it such corrections as it may require."(81) It appears that this was complete in July 1831, and the Council authorised it to be printed, although this does not seem to have been done.(88)

As with the 1827 inventory, the 1831 list survives in more than one form. It is usually identified with the instrument maker William Simms (1793-1860, F.R.S. 1855), who assisted in its preparation.(89) The earlier version of this comprises 81 numbered items, the last marked "Mr Simms to inspect it", and is presumably in the form of Simms' original catalogue.(90) A later version has each item identified by two numbers: "No in Simm's Catalogue" and "Proposed Number", the first of which refers to the earlier version.(91) The list has been annotated and has clearly been used as a working copy in preparing a printed version. The final page, which has been marked "not to be printed" is headed "Report by Mr Simms (May 1831)" and describes the physical condition of some items, ending "In conclusion, - the most important & useful instruments are those that I find are in the best condition." The majority of historically interesting instruments are included amongst

"Those of apparent utility", although some, including Wilkins' 1663 burning lens, were in a separate section of "Those apparently useless".

In November 1831 new regulations were approved enabling the Council to restrict the borrowing of instruments and place the onus for their safety and their return within a specified period on the borrower.(92) It was now agreed that a definitive list of instruments was to be drawn up and the Treasurer (Lubbock) was "authorised to dispose of whatever instruments or materials may be found to be useless to the Society." In order that the items should be readily and permanently identifiable the Council also resolved "that, as far as circumstances will permit, each instrument be marked with the words "Royal Society" or the letters "R.S.", and each detached part be marked with the number corresponding to that in the catalogue". It is not clear when this numbering was done, but it is likely to have been in early 1832.(93)

After some delay, the printed catalogue of the instruments appeared in late 1834, with the new numbering.(94) Although Kater and Lubbock had retained a few of the items that Simms had recommended as 'useless', the majority had now gone, including the intriguing parcels of "unimportant sundries".(95) The Newton telescope, which had been given a proposed number of 22 in 1831, was engraved with the number 28 that subsequently appeared in the 1834 list. It is described in the printed list as having "4 parts", but it is not known what these were, or whether they included the additional objective speculum.

Having now regularised the instrument collection, the Council showed increasing reluctance to place historical material at risk. The astronomer W.H. Smyth was told in 1843 that the Council did not wish "to make a precedent for removing from the Apartments of the Society so valuable an instrument as the telescope made by Sir Isaac Newton";

and in the same year the Royal Institution was told that "it is the practice of the Council to refuse to allow instruments possessing any value as historical records to be taken out of the Apartments of the Society".(96) An exception was however made for the Government's 1875 Special Loan Collection of scientific apparatus at South Kensington, but the Newton telescope has retained a special significance for the Royal Society and it was not amongst the apparatus subsequently lent to the Science Museum.(97)

Notes and References

1. For the early history of the Society and its Repository see for example Birch (1756-7), Hartley (1960), Lyons (1944), Purver (1967) and Weld (1848). The Society's occupancy of Gresham College is discussed by Adamson (1978).

2. Sprat (1667), 93.

3. Adamson (1978), 5.

4. See for example Bennett (1980), Gunther (1930) and 'Espinasse (1956). Hooke's appointment as Keeper was made on 19 October 1663: "It was ordered, that Mr HOOKE have the keeping of the repository of the Society, for which the west gallery of Gresham College was appointed": Gunther (1930), 157.

5. Grew (1681), imprimatur: the meeting of 18 July 1678 is unrecorded in the Roy. Soc. MS Council Minutes. An earlier inventory, apparently restricted to purchased items in the Repository, was prepared in 1663. Hooke was instructed to produce a further catalogue of "all the instruments or other apparatus of the society, paid for out of the public treasury" in December 1674. At that time also the instruments were to be "looked out and kept together in the repository for instruments", which was clearly a separate room. Hooke's catalogue presumably materialised, since when the Society regained full use of its accommodation in Gresham College in early 1675 Hooke was ordered to move the collections and 'perfect' the catalogues. Whether Hooke developed a systematic classification for the collections is unknown, and no catalogue by Hooke has been located. Gunther (1930), 160, 426, 429.

6. Grew (1681), 360, referring to Phil. Trans. R. Soc. Lond. 7 (1672) 4004-7. Although Grew provided no new information about the telescope to demonstrate that he had examined it, it must be assumed that it was indeed in the Repository in 1681. The same is not necessarily so in 1686 and 1694 when subsequent editions of the catalogue appeared since these were merely reprintings of the original text, with even the corrigenda uncorrected.
7. Lyons (1944), 90.
8. The terms of Grew's appointment are recorded in Weld (1848) I, 280. For Hunt see Robinson (1946), 196: this article was written in 1939 and used extensively in Lyons (1944).
9. Robinson (1946), 197, notes that the Society owed Hunt at his death £650 plus interest.
10. Mayor (1911), 313.
11. Quarell & Mare (1934), 98.
12. Mayor (1911), 379.
13. Hatton (1708) II, 666. The comparison between Hatton's listing and material known to survive in the 1730s refers to manuscript inventories to be discussed below.
14. The reflecting telescope may have been involved in at least one move before the transfer to Crane Court in 1710. From 1667 to 1673 the Society met at Arundel House because Gresham College was required for use as a temporary Exchange. The West Gallery at Gresham, in which the Repository had been housed, was however not returned to the Society's use until 1675. In spite of inference to the contrary in Weld (1848) and the Royal Society Record (1940) it appears that the Repository remained at Gresham.

A new location was found for it by Hooke, where it must have been effectively in store, and on 22 June 1668 the Council reimbursed him "for fitting the place in Gresham College for the societys repository": Roy. Soc. MS Council Minutes. The instruments certainly remained under Hooke's control at Gresham, and one of the principal reasons given for the eventual return to Gresham was "the conveniency of making their experiments in the place where their Curator dwells, and the apparatus is at hand": Weld (1848) I, 241. This is not inconsistent with the brief account of the Repository at this time by Lorenzo Magalotti who appears to link it with Arundel House. Magalotti attended a meeting of the Society in Arundel House in 1669, accompanying Cosimo III, but the only objects described by him were those actually exhibited at the meeting: Weld (1848) I, 218, quoting Magalotti <u>Travels of Cosimo III, Grand Duke of Tuscany ...</u> (London 1821).

15. Adamson (1978), 7.
16. Roy. Soc. MS Council Minutes, meeting of 8 September 1710.
17. Bennett (1972-3), 108.
18. Roy. Soc. MS Council Minutes, meeting of 8 April 1712.
19. White (1936), 57. Stukeley claimed to have begun his collection in 1726 when he moved to Grantham, and in the following year he sent a long memoir on Newton to Richard Mead, Newton's physician, under whom Stukeley had studied when first in London. This was intended for transmission to John Conduitt for his proposed biography of Newton, but as it covered only Newton's early years in the Grantham area there is no mention of the telescope: Nichols (1817-31) IV, 23. This, and other material sent by

Stukeley to Conduitt, became inaccessible to Stukeley after Conduitt's death in 1737, and it passed by descent into the possession of the Earl of Portsmouth. Access was granted to John Nichols, but of the portions he published only James Rutty's 1722 extracts from the Society's journal books related to the telescope: ibid IV, 19. Hence although it can be deduced that Stukeley's 1752 biographic sketch was written largely from recollections, no earlier account by Stukeley of the telescope has been found to indicate when it was seen. However, the reference to the telescope and the burning glass is quite specific and it must be assumed that Stukeley saw both instruments: although Piggot (1950) has questioned Stukeley's objectivity in the period in which the manuscript was written, he is likely to have been correct in such a factual matter. Stukeley was not unfamiliar with astronomical instruments; and he served for example as a member of the Board of Visitors of the Royal Observatory, Greenwich, in 1726: Forbes (1975), 83. He also is known to have taken an interest in the Royal Society's Repository, chairing the Repository Committee on three occasions during the reorganisation of 1731 when geological specimens were being considered: Roy Soc. MS 490 (CMB 63). It is unfortunately not possible to narrow down the period in which the telescope was seen since it is known from his diaries that Stukeley was attending Royal Society meetings regularly after his return to London in 1748 and occasionally before then: Lukis (1882-7). However, since it will be demonstrated below that the telescope and burning glass had deteriorated by the 1730s it will be assumed that both were seen by Stukeley before his departure for

Grantham in 1726, and most probably shortly after coming under Newton's influence in 1718. His account confirms that the telescope survived until at least 1718.

20. Mills & Turvey (1979), 141, following the transcription from the 1739 translation of Algarotti's Il Newtonianismo per le dame quoted in Nature 143 (1939) 110.

21. Algarotti (1739) II, 129.

22. Roy. Soc. MS Council Minutes: meeting of 7 December 1713.

23. 'The Report of the Committee Appointed to Inspect the State of the Library's and Repositry' bound in ibid at meeting of 27 June 1723. Thomas had in fact been instructed twice by the Council in April 1719 to prepare a catalogue which was to be in the form of an interleaved copy of Grew's catalogue with the descriptions brought up to date: ibid, meetings of 8, 23 April 1719. It is possible however that some work may have been done in the Repository: the Rev Moses Williams (FRS 1719), who acted as temporary housekeeper until Thomas' successor was chosen and who was later unsuccessful in his application to become Keeper of the Library only, claimed to have "been conversant in the Society's Repository in Mr Thomas' time": ibid, meeting of 4 April 1723. He was also invited to join the Council's 1723 Repository and Library Committee: ibid, meeting of 9 May 1723. The easy assumption by Williams of Thomas' duties immediately after the latter absconded suggests that Williams may have been the assistant which Thomas was required to employ from 1719: ibid, meeting of 8 April 1719. See below, ref (37).

24. Idem. A bricklayer's bill for work done in the Repository in 1724 may have been for the installation of the chimney that was certainly in place by 1734 - this however was only lit on meeting days and proved inadequate: ibid, meeting of 18 February 1733/4. An apparently equally intractable problem was the offensively strong smell of the cheese stored in the cellar below the Repository - it took five years of agitation to evict the cheesemonger who had leased the cellar!

25. Ibid, meeting of 9 May 1723.

26. Guerlac (1964).

27. Roy. Soc. MS Council Minutes, meeting of 27 June 1723.

28. Ibid, meeting of 3 July 1729.

29. Roy. Soc. MS 490 (CMB 63), meeting of 8 May 1733.

30. 'The Report of the Committee for inspecting the State of the Repository and Libraries of the Royal Society' dated 9 October 1729, in Roy. Soc. MS Council Minutes, at meeting of 6 Nov 1729.

31. 'The Report of the Committee appointed to inspect and Examine into the State of the Repository of the Royal Society', in ibid, at meeting of 18 February 1733/4. The Report apparently dates from just before the Council's 29 October 1733 meeting at which it was first read, but it was not subsequently amended to note the completion of the examination of the artificial curiosities on 30 October.

32. 'Report of the Committee for Examining the State of the Repository of the Royal Society' in ibid, at meeting of 2 November 1731.

33. See above, ref (31).

34. Roy. Soc. MS Council Minutes, meeting of 12 January 1735/6.

35. Roy. Soc. MS 490 (CMB 63), MSS 413, 414, 416 (known respectively as Catalogues A, B and D).

36. Roy. Soc. MS Council Minutes, meeting of 6 November 1729.

37. The catalogue is divided along lines closely similar to those used by Grew, and lists the items noted by Grew with subsequent donations to about 1719 interspersed in the earlier part. Later donations to about 1725 have been added in a manner that suggests it was used as a running catalogue until about that date. It seems likely that it was the work of Moses Williams, who would presumably have protested its unofficial status to the 1723 Committee. Confirmation that it continued to be used as the principal catalogue in 1731 is provided by the additions made by the Committee in that year. Similarly, of the later sections, only that on corals has the entries individually numbered, and it was noted in June 1733 that John Martyn, who had served on the 1730 Committee, "did formerly at ye Desire of ye Committee examin & number ye Corals": Roy. Soc. MS 490 (CMB 63), meeting of 15 June 1733. The Catalogue has previously been incorrectly dated as 1763/4 on the evidence of watermarks. The early numbered copy of Grew's catalogue mentioned by the Committee cannot be located, but the Committee appears also to have been using the incomplete copy of the first impression now in the Royal Society Library. In this the individual entries are distinguished in pencil and the first 80 pages of the catalogue section (covering the review period up to the beginning of the minuted meetings) have been cut out.

38. Roy. Soc. MS 490 (CMB 63), meeting of 22 July 1731.

39. Ibid, meeting of 29 July 1731, item 7.

40. Ibid, meeting of 16 September 1731.

41. Roy. Soc. MS 416 (Catalogue D): 'A Complete Catalogue of the Several Donations of Manuscripts, printed Books, Naturall Curiosities, Machines & Antiquities, which have been presented to the Royal Society, extracted from the Journal Books with the dates when given & the Donors names annexed". The list was kept up to date until early 1737: it is continued in MS. 419 which runs to 1744.

42. Roy. Soc. MS 414, untitled. This had been dated on the evidence of watermarks to c1741, but is certainly of 1732-3.

43. Roy. Soc. MS 490 (CMB 63), meeting of 30 October 1733.

44. Items that did not appear on Mortimer's list (normally because they were incomplete or unidentifiable) were added at the end of the relevant section. At the last meeting of the review about 100 trifling items remained and only a few of these could be adequately identified. The available space for additions to some sections (such as 'optics') had by then been used up. The majority of these last items, including the two Newton specula, are listed on two loose sheets of paper inserted at the end of MS. 414.

45. Roy. Soc. MS Journal Book, meeting of 20 June 1728. The lens was borrowed in February 1712/3 by William Derham, and then from 1718 was remounted and used by John Pound assisted by Bradley: Atkinson (1952), 387, 388.

46. Roy. Soc. MS Council Minutes, meeting of 24 June 1728. The other objectives were one of 170ft focus which had been in Newton's possession and another of 210ft focus presented by Gilbert Burnet

in 1724. These were described by Sampson & Conrady (1928-9) who concluded that all three lenses owned by the Royal Society were the work of Constantine Huygens rather than his brother Christiaan.

47. The lenses survive, and are at present on loan to the Science Museum, London. The microscopes were later lent to Henry Baker who returned them in 1741, and they were subsequently kept in the Repository, from which they eventually disappeared.

48. See for example Desaguliers (1735).

49. See above, ref (31).

50. Roy. Soc. MS Council Minutes, meeting of 16 September 1734.

51. Ibid, meeting of 12 January 1735/6.

52. Ibid, meeting of 13 September 1737.

53. Ibid, meeting of 31 January 1738/9. It would appear that Mortimer's catalogue was not yet complete. It is not known whether this inventory was drawn up, and no copy signed by Hauksbee survives in the Royal Society.

54. Lukis (1882-7) I, 372.

55. Whitehead (1977).

56. Ibid, 7.

57. Roy. Soc. MS Council Minutes, meeting of 3 April 1763.

58. Whitehead (1977), 8; Brock (1977), 259.

59. Harris (1704-10) II, article 'Burning Glasses'.

60. Amongst the items listed in their final session by the 1733 Repository Committee was (number 238) "a set of reflecting concave glasses one broken" which may be the individual components of the burning glass: Roy. Soc. MS 414.

61. This item when first listed in 1731 was described as "Sir Isaac Newton's Apparatus for making observations at Sea by a double reflection" with "Query" added, but was amended to "A Wooden Quadrant with Sliding Index": MS 490 (CMB 63), meeting of 12 August 1731, item 85. It is of interest that the initial attribution was made, since only three months beforehand Mortimer had examined the Journal Books for the 1699 description of Newton's instrument in order to assess whether Newton had priority over John Hadley. The 1731 entry in MS 414 was "a wooden model of Dr Hook's Reflecting Quadrant", and it was numbered 14 in 1733. An entry "Large wooden Quadrant" in the 1765 catalogue (MS 417) had added "Q^{r} if No 14", but it is not known if this was confirmed: the item does not appear subsequently.

62. Roy. Soc. MS Council Minutes, meeting of 17 March 1763.

63. Roy. Soc. MS 415, f1.

64. Roy. Soc. MS 417: 'An Inventory of such Antiquities, Machines, Models, Mathematical and Optical and other Instruments, Weapons of War, Apparel, Utensils and curious Works of Art, as are now in the Repository of the Royal Society. Nov.^{r} 21 1765'.

65. Roy. Soc. Journal Book, meeting of 21 November 1765.

66. Roy. Soc. MS Treasurer's Papers (Uncatalogued). Four accounts for da Costa's expenses are for the periods Jan 1764 - Nov 1764, Dec 1764 - Nov 1765, Jan 1766 - Nov 1766, Dec 1766 - Nov 1767.

67. <u>Ibid</u>, entry for 27 June 1764. The wording is of course ambiguous in that it may refer to an internal reorganisation of the Repository, but is distinct from that of entries describing general assistance in the Repository.

68. See above, ref (39).

69. Robinson (1946), 201.

70. Plans showing the proposed museum accommodation are preserved as Roy. Soc. MS MM. 13.58.

71. Weld (1848) II, 120.

72. The Picture of London for 1806 (London 1806), 157.

73. It is possible that the instruments, models, etc, had already been separated from the natural history collections by the time the gift to the British Museum was proposed. Such a separation was proposed in 1737 (Roy. Soc. MS Council Minutes, meeting of 13 September 1737) but may not have been acted upon. It is not clear how the Repository collections were divided in 1780: the acknowledgement from the British Museum Trustees of June 1781 notes the receipt only of "the very ample collection of natural productions", whereas Weld was able to trace some specimens of comparative anatomy to the Museum of the Royal College of Surgeons of England: Weld (1848) II, 125. Both the Picture of London for 1806 and the Original Picture of London enlarged and improved of 1826 say the Society had a museum of natural history.

74. Howse & Hutchinson (1969), 282.

75. Roy. Soc. MS Council Minutes, meeting of 8 February 1827.

76. Lyons (1944), 244, 248.

77. Kater (1818).

78. Roy. Soc. MS DM.2.124, 'Account of Instruments, Aparatus, and Coins belonging to the Royal Society. March 1827'.

79. Roy. Soc. MS DM.2.126, untitled, 1826 dated watermark.

80. In the principal copy the word 'concave' has been amended in pencil to 'flat' (and this clearly shows that it cannot be a

component of Newton's 1704 burning speculum), but then the whole entry has been deleted in pencil and "with addition obj. mirror" inserted against the entry for the telescope: ibid, f2. These amendments are in a different hand to that of the original entries, and perhaps date from the 1831 cataloguing.

81. Roy. Soc. MS Council Minutes, meeting of 26 April 1827.

82. Lyons (1944), 250.

83. Ibid, 256.

84. South's original letter to the President of 5 April 1855 noted that the Society's correspondence was lacking for the entire period 1740-1830, and that one of the Society's officers had stated that the microscopes were lost (Roy. Soc. MS MC.5.198). In a further letter of 28 July South said that he had been told by a previous Assistant Secretary (at some time before 1826) that the microscopes had been lent to Home: South had recently examined instruments supposed to have been made by Leeuwenhoek, and therefore perhaps the Society's, but he had found that they were not by Leeuwenhoek (MS MC.5.207).

85. Royal Society Record (1940), 168.

86. Roy. Soc. MS Council Minutes, meeting of 3 March 1831.

87. Ibid, meeting of 9 June 1831.

88. Ibid, meeting of 7 July 1831.

89. Howse & Hutchison (1969), 288, however mistakenly associate the 1827 list with Simms.

90. Roy. Soc. MS DM.2.123, untitled.

91. Roy. Soc. MS DM.2.127, 'INSTRUMENTS belonging to the Royal Society 1831'.

92. Roy. Soc. MS Council Minutes, meeting of 10 November 1831. Two weeks later the account for preparing the catalogue was approved: "Resolved that the following bills be paid ... Troughton & Simms, for making a list of the instruments in possession of the Society, &c. £6.12.6": ibid, meeting of 24 November 1831. Although the Council resolved to print the regulations for the loan of instruments (as well as books) to be printed, no copy has been found: ibid, meeting of 22 December 1831.

93. The work was to be supervised by the instrument maker George Dollond (1774-1852, F.R.S. 1819) who at the time was constructing Peter Barlow's fluid-filled lens telescope for the Society. No separate account was submitted, but it may have been added to his bill for the telescope which was approved on 14 February 1833: ibid. The inclusion of new and unnumbered items in the list when it was published in 1834 suggests the numbering was done some time before; as does the fact that one item (the Shelton regulator, item 33) is identified with a piece that bears no number (Howse & Hutchison (1969)), but which was apparently away from the Society's rooms in early 1832 under test by Francis Baily. Dollond subsequently explained to Lubbock that he had only been able to mark those instruments in the rooms or which had been borrowed by members of the late Board of Longitude: Roy. Soc. MS LUB.D.202.

94. Instruments and Apparatus belonging to The Royal Society. The Council ordered the printing of this and of the portrait list on 16 October 1834, and both are dated November 1834.

95. A single sheet with the Simms inventory lists a number of items including "2 Specula for I. Newton's Telescope": Roy. Soc. MS DM.2.129. It is clear that this list, on 1830 watermark paper,

is of items that were looked for in vain, and that do not appear in the 1827 inventory.

96. Royal Society (1832-46), 410, 413.

97. Roy. Soc. MM13.49.

3.6c Some Problems with the History of the Heath Telescope

The problem about drawing conclusions from the Royal Society's telescope is that its history is unknown. It immediately raises three questions: where did it come from, to what extent may it be Newton's work, and to where did the Society's original Newton telescope vanish? Unfortunately there are too many possibilities, some of which are outlined below, to enable any of these questions to be answered at present.

The 1766 presentation by Thomas Heath was made through George Scott rather than through any of the Fellows more normally associated with astronomy or the instrument trade. This may suggest that he was connected in some way with the instrument, perhaps even having helped Heath to acquire it initially. George Scott (1720?-1780, F.R.S. 1748) was a passionate antiquarian from Chigwell in Essex, very close to Wanstead where James Bradley was brought up. It was Bradley who proposed him for fellowship at the Royal Society, describing him as a "Gentleman well versed in Natural Knowledge."(1) Scott was a nephew of William Derham (1657-1735, F.R.S. 1702) the versatile author of The Artificial Clockmaker and editor of the papers of the naturalist John Ray. Derham's considerable collections passed to his son, a Fellow of St. John's, Oxford, and included "all my Books Telescopes and Telescopic Glasses of all the several lengths and all other Mathematical and philosophical Instruments".(2) On the death of William Derham junior in 1757 these collections passed to his cousin, George Scott, whose description of them however included 'mathematical instruments' but not specifically telescopes. Certainly, if the telescope displayed by Heath came from this collection it would have left the care of Derham junior before the collection was inherited by Scott. Scott published some of the writings by Ray that he had been left, but his interests seem to have been directed principally to antiquarianism. His collection was dispersed after his death, but instruments are not included in the list of the divisions of the collection which was made by E.M. da Costa at the time of the sale.(4)

There are several points of contact between the Derhams and early experimenters in reflecting telescopes. Firstly, Robert Hooke's apparatus and papers had passed to Richard Waller and it was "amongst ye late Dr. Hooke's Optic Glasses" that Waller discovered Hooke's reflecting microscope.(5) The papers, and presumably also the apparatus, went to Derham after Waller's death, and from these Derham published the Philosophical Experiments of Robert Hooke in 1726.(6) Derham was also familiar with James Bradley and Samuel Molyneux, both of whom experimented with reflecting telescopes under John Hadley's guidance in the 1720s. He corresponded with Molyneux, with whom he shared an interest in improving "Sir Isaac's Catoptrical Telescope", and he probably owed his position as chaplain to the Prince of Wales, and later as Canon of Windsor, to Molyneux's influence.(7) It should be noted that Derham was frequently pleading poverty and attempting to borrow instruments from friends, and that he appeared to have ready access to the Royal Society's collection through Sir Hans Sloane.(8) It is possible therefore that the Newton telescope was borrowed from the Society and only its mirrors returned in time to be included in the 1731 catalogue of the Repository.

A second possible provenance route is through Edmond Halley. The small reflecting telescope which Stone described as being in

Thomas Heath's shop was not the only item supposedly by Newton that Heath had. In his description of Hadley's reflecting octant Stone noted that:

> "The first of these Instruments for taking the Moon's Distance from the fixed Stars was invented long ago by Sir Isaac Newton, as appears in a Paper of Sir Isaac Newton's own Hand-Writing, found amongst those of the late Dr Halley, and the very Instrument itself that Sir Isaac Newton either made himself, or caused to be made so long ago as when Dr Halley went about making the Catalogue of the fixed Stars in the South-Seas, which was the Year 1672, was not long ago to be seen at Mr Heath's the Mathematical Instrument-Maker in the Strand. See the Philosophical Transactions, Number 465, for the Year 1742". (9)

There is little doubt that Newtonian relics of this calibre would have been highly prized around 1750 and the chance of their having been acquired by Heath from separate sources seems rather remote. It may then be that the telescope had the same provenance as the quadrant.

Newton's reflecting quadrant has been described on a number of occasions, most recently by C.H. Cotter, but the only analysis of Stone's account has been by S.P. Rigaud.(10) However, Rigaud was unaware of how Newton's instrument related to an earlier one by Edmond Halley, and as a result he was quite incorrect in his conclusions. Halley's <u>Catalogue of the Southern Stars</u> was compiled from observations made at St. Helena, in the South Atlantic, in 1676-8 (and not 1672). Stone probably confused this well-known expedition with Halley's voyage round the South Atlantic in 1698-9, whose object was coastal and magnetic surveying. Halley may well have used a reflecting instrument rather than a backstaff for latitude determinations since he had described such an instrument "for observing at Sea" at the Royal Society in early 1692.(11) A single mirror was placed at the objective end of a small telescope, partly obscuring its direct view, and was attached to an arm moving over a scale showing the mirror's inclination to the telescope axis: by turning the arm an object viewed in the mirror was "seen to coalesce in the same point" as one viewed directly. The germ of the idea may have come from a discussion with Hooke ten years beforehand[(12)], and when Halley's instrument was described Hooke was quick to claim priority for his earlier design, "the Modell of which he produced out of the Repository". Halley however thought the instrument sufficiently promising that he arranged to have it made in wood "for tryal and practice, and design one of brass for use."[(13)]

Halley returned to Britain in mid 1699, and was present at a Royal Society meeting in August, immediately before setting off for another Atlantic voyage, when

> "Mr Newton shewed a new instrum$^{t.}$ contrived by him, for observing the moon, stars, the longitude at Sea, being y^{e} old instrum^{t} mended of some faults, with which notwithstanding Mr Hally had found ye Longitude, better y^{n} y^{e} Seamen by other methods." (14)

When John Hadley's reflecting quadrant was exhibited in May 1731 Halley observed that Newton had already invented a double reflecting instrument on the same principle and had "communicated some Account of it to the Society in the year 1699".[(15)] The version given later by William Wales was that

> "at the time when Mr. Hadley's paper was read, Dr Halley did declare he had one [such paper] of Sir Isaac Newton's, describing an instrument similar to Mr. Hadley's and which was given him in 1700 or 1701, but that he did not then know where to find it." (16)

Several months later Halley unexpectedly announced that Newton's instrument was indeed different from Hadley's, so perhaps he had now found the paper.[(17)] Certainly it turned up after his death in 1742 and was presented to the Society by the executors, and was subsequently published in the Philosophical Transactions.[18]

It seems likely that Newton's account of his reflecting quadrant, which is for a 3 to 4 foot radius instrument of brass, was given to Halley after his return from his second Atlantic voyage in late 1700. It appears to be a proposal for the design for an instrument, rather than a description of a specific quadrant. So if Newton did show such an instrument in 1699, it may well have been a model intended to demonstrate the principle. It may be conjectured that Newton lent this model to Halley also, or perhaps Halley had one made for use in his 1701 charting of the English Channel. His subsequent admission that the invention had not proved satisfactory at least implied that it had been tried.[19]

Halley enjoyed a privileged relationship with Newton, who respected his abilities. It had been Halley who had persuaded Newton to write the Principia, who circumvented the criticism of Hooke and had steered the first edition through the press. Following Newton's illness in the early 1690s, and his appointment as Warden of the Mint, Newton turned to Halley to assist with the recoinage at Chester. Halley was close enough to Newton for it to be easy to imagine his borrowing or being gifted Newton's third reflecting telescope. Similarly, Halley could readily have borrowed the Royal Society's instrument.[20]

Edmond Halley's Tabulae Astronomicae were published posthumously by his friend the astronomer John Bevis (1693-1771, F.R.S. 1765), who had assisted him at Greenwich in observing the 1736 transit of Mercury. Bevis was in regular correspondence with James Bradley, and his interest in reflecting telescopes led him to play a prominent part in trials conducted in 1736.[21] He was closely associated with a number of instrument makers, including Thomas Heath, who was present at the 1736 trials and to whose house Bevis was in the habit of having his correspondence directed.[22] Although one may conjecture that he obtained instruments such as the Newtonian reflector and quadrant from Halley, he played a more certain part in the disappearance of one of Newton's telescopes, and, since he acted as one of the Royal Society's Secretaries from 1766-72, this may have been the Society's 1671 instrument. G. L'E. Turner has pointed out that such a telescope was included in the 1785 sale of the library and instruments of Bevis and of his friend and executor James Horsfall (F.R.S. 1768).[23] The telescope was especially described on the title page of the catalogue: "Among the Instruments is Sir ISAAC NEWTON'S Reflector, which he used in many of his Astronomical Observations". It was entered as "Sir Isaac Newton's Reflector, defective", indicating perhaps that the mirrors were missing.[24]

Francesco Algarotti's reference, already quoted, to having seen the "first telescope ... preserved in a city of England" in 1736 may mean that he saw the instrument that was later presented by Heath.[25] He continued that "with this are treasured up those prisms" with which Newton first interpreted the effect of dispersion. I.B. Cohen has pointed out that the story of the supposed gift of such prisms to Algarotti by Catherine Barton Conduitt in 1736 arose only at the end of the century and after Algarotti's death.[26] Rather than argue for the telescope and the prisms having remained in Newton's family, I would suggest that Algarotti's "city in England" may have been Cambridge. Robert Smith was at the time finishing his great Compleat System of Newtonian optics. Smith had lived with his uncle Roger Cotes, and had succeeded him as Plumian professor of astronomy. He had retained the considerable correspondence between Newton and his uncle, who had revised and published the second edition of this Principia for him, except for some letters lent to John Conduitt for his projected life of Newton and not returned. The library of Trinity College had a number of 'authentic' Newton relics in the early 19th century and these may well originally have been in Smith's care.(27) It is possible that Newton's third telescope passed into the hands of Cotes and then Smith, but it is more likely that if Smith had a small Newtonian telescope it would be one of Molyneux's early reflectors.(28) A Newtonian instrument which might answer to the description of this was sold in 1794 as being made by Sir Isaac Newton and one can appreciate how Algarotti might have been similarly mistaken.(29)

Notes and References

1. Roy. Soc. MS Certificate Book, Vol 1 (1735-51), No 359. Scott's membership is not noted in the biographical account by Searle (1966).
2. Atkinson (1952), 391, citing Derham's will of 1733.
3. Searle (1966), 193.
4. Nichols (1812-6) IX, 813.
5. Roy. Soc. MS Journal Book, meeting of 5 April 1711.
6. The manuscripts were kept together until 1890 when they were dispersed at the sale of Moor Hall, Essex: Aked (1970), 501. Whether instruments were sold at this time is not known, and no catalogue of the sale has been located.
7. Atkinson (1952), 384, 386, 388.
8. For example, the loan of the Huygens 123ft lens was acknowledged to Sloanein 1713: ibid, 387 n184.
9. Stone (1758), 268.
10. Cotter (1978); Rigaud (1833-4), 659-61.
11. Roy. Soc. MS Journal Book, meeting of 23 March 1691/2.
12. Macpike (1932), 185, citing Hooke's diary entry for 10 March 1682.
13. Ronan (1970), 130: preliminary remarks to an unpublished 1692 Royal Society paper on a coelostat.
14. Roy. Soc. MS Journal Book, meeting of 16 August 1699.
15. Ibid, 30 May 1731.
16. Rigaud (1833-4), 660, citing Wales' Original Astronomical Observations of 1777.
17. Roy. Soc. MS Journal Book, meeting of 16 Dec 1731.

18. Newton (1742). William Jones, on behalf of the executors, initially provided only a copy (Roy. Soc. MS L&P I. 120) which was used for publication: Roy. Soc. MS Journal Book, meeting of 28 October 1742. Newton's undated original, which was not seen by Rigaud, is now Roy. Soc. MS MM.16.110. (The watermark is Heawood's 454 of 1700 or 455 of c.1698).
19. Taylor (1966), 192.
20. On Halley's death, his executors returned a number of volumes that belonged to the Society: Roy. Soc. MS Council Minutes, meetings of 21 June and 5 November 1742.
21. Roy. Soc. MS LBC.23.88-95.
22. Rigaud (1832), 416, 425: letters of Bevis to Bradley, 27 April 1739, 24 December 1743.
23. Turner (1969), 107 n44; the sale catalogue is Paterson (1785); for Horsfall as excutor see Bernoulli (1771-6) II, 331.
24. Paterson (1785), 24, lot 2*. It sold for a mere 8/-.
25. See the preceding section.
26. Cohen (1957), 214.
27. Price (1952), 6.
28. Clerke (1894), 136.
29. Christie (1794), 7: lot 29 "An original 2-feet mahogony reflecting telescope on a stand, made by Sir Isaac Newton". I am indebted to Mr A.J. Turner for this reference.

3.7 CASSEGRAIN'S PROPOSAL AND THE DEBATE OVER OPTICAL SYSTEMS

Newton's new telescope was prominently reported in the French scientific journals in early 1672. The Journal des Scavans carried a description and illustration together with a commendation from Huygens towards the end of February: this was followed immediately by an enthusiastic account in the third of J.B. Denis' Mémoires. It appears to have been the latter that prompted a letter to Denis from a M. Henri de Bercé of Chartres, in which he put forward a claim on behalf of a M. Cassegrain to have invented a design of reflecting telescope before that of Newton. Almost nothing is known of Cassegrain, and he is variously identified as professor of physics at the College de Chartres or as one Guillaume Cassegrain (fl. 1666-84), a sculptor and founder in the service of Louis XIV.[1]

Cassegrain's interest had apparently been aroused by the extended account of Samuel Morland's loud-speaking trumpet which had appeared in the first two Mémoires earlier in the year. His own proposals for the proportions of such a trumpet were sent to de Berce for transmission to Paris. In his covering letter de Bercé took the opportunity to say that Cassegrain had also invented a reflecting telescope:

> "The telescope of Mr Newton surprised me as much as it did the same person who found out the proportions of the trumpet that I sent you, because about three months ago he sent me the figure of a telescope, which is almost the same and which he invented, but which I find more ingenious." (2)

The description which de Bercé gave was for an instrument which differed from Newton's in having a convex secondary placed so as to intercept the convergent cone of light from the objective and reflect it back through a hole in the centre of the objective to an eyepiece.

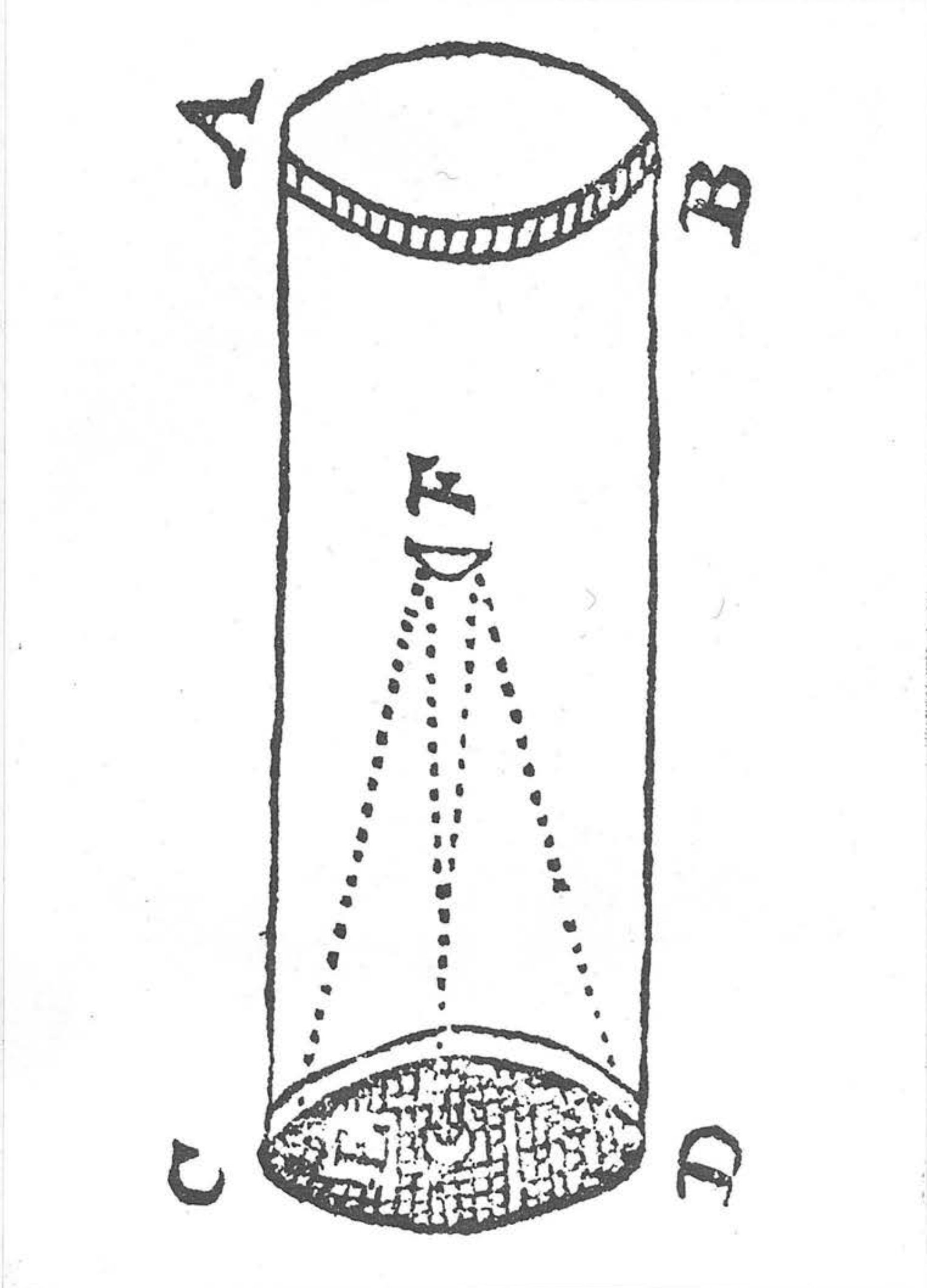

Fig. 4. Cassegrain's reflecting telescope of 1672: de Bercé's sketch reproduced in the Philosophical Transactions from the original publication in Denis' Mémoires.

The date of the letter is not known, but it presumably was not long before its publication by Denis in the Mémoire of 5 April; although the telescope letter could be printed, there was apparently no room for Cassegrain's paper on Morland's trumpet, which was deemed less important and held over until the following issue. By dating his receipt of Cassegrain's 'figure' to a few weeks before the publication of Newton's design, de Bercé made a claim for his countryman's priority that many no doubt saw as transparent or at least highly suspect. Not only this; de Bercé proceeded to insinuate that it was superior to Newton's in four points. The aperture he claimed could be any size required; the reflections were in the direction of the axis and therefore were natural and lively; the observer was not troubled by extraneous light since his face was masked by the base of the tube; and lastly, it was easier to direct to objects. There was no suggestion that Cassegrain's telescope had ever been constructed, and no further evidence was advanced when the device was sharply criticized in other journals by Huygens and Newton.(3) Denis and de Bercé were content to let the matter drop in the face of scathing comment.

Oldenburg copied the extract from the Mémoire for Newton asking for an answer to send to "those Parisian Refiners". In particular, now that Hooke had reminded the Society of Gregory's early work, Oldenburg wanted Newton to compare Gregory's proposal with that of Cassegrain, and he was satisfied that Newton would "find cause to controle the confident assertions of the Author".(4) Regardless of whether or not Newton was already familiar with Gregory's Optica Promota, he now had to demonstrate the superiority of his own design over both the others, and this he found no difficulty in doing.[5] Newton explained that once he had begun to consider reflecting instruments, he had come across Gregory's proposal, but, finding the disadvantages of instruments of this type so great, he had had to alter the design and place the eyepiece at the side of the tube.[6]

The several disadvantages of Cassegrain's design that Newton enumerated were therefore all criticisms of the use of the convex secondary, but applied equally to Gregory's concave mirror. Less light, Newton pointed, out, was lost in the reflection from his inclined mirror since "it is an obvious observation yt light is most copiously reflected from any substance when incident most obliquely". The hyperbolic form strictly required for Cassegrain's secondary before it would perform as well as Newton's flat mirror was vastly more difficult to fashion, but even if this could be done it would not perform accurately except for points precisely on its axis. The errors in its figure would be hard to avoid and they would become more obvious because the design required the mirror to be a greater distance from the eyelens than in his design. It would also tend to compound the errors in the figure of the primary mirror: in particular, it would amplify those errors that resulted from the primary having a spherical rather than a parabolic figure, and this would mean that the aperture would have to be less than in Newton's instrument. The most unexpected contention was that, since the secondary contributed to the magnifying effect, the instrument would necessarily be over-charged and the images therefore "very obscure & darke". His doubtful justification for this was that the secondary could not have a larger radius of curvature without cutting off too much incoming light, and a low power eyepiece could not be used without seriously restricting the field of view.

Newton then demolished the remaining advantages proposed for Cassegrain's telescope, discussing the supposed "natural" nature of the reflection along the axis of the secondary by the curious device of noting that the axis itself was reflected by the secondary of his own instrument. The masking of light from the observer's eye was clearly a trivial point.

The conclusion for Newton was clear: "ye advantages of this designe are none, but ye disadvantages so great and unavoydable that I feare it will never be put in practice with good effect." In fact, he continued, because Cassegrain's design was more obvious than his own, it would have been tried first by others attempting to make reflecting telescopes and this would explain why no-one (except himself) had yet had any success. As if to confirm this, he cited the passage from Gregory's book, which was discussed in an earlier section, about vain attempts to produce non-spherical surfaces, and repeated what Hooke had said about the instrument Reeves had made for Gregory. This instrument must have been to Gregory's published design, he stated, if merely because "though made by a very skilful Artist, yet it was without successe". His parting shot was a patronising warning to Cassegrain that "such projects are of little moment till they be put in practise".

Newton's devastating attack, although it succeeded in its object of dispatching Cassegrain, was less than fair. At least part of his criticism lay in an insinuation not only that Cassegrain's attempt was deficient in that non-spherical lenses were not attempted, but also that Newton had the skills required for the most exacting work; and yet this was done without admitting, except in a very veiled manner, that Newton himself had used spherical surfaces. His analysis of the magnifying effect of the secondary and the restricted field of view is misleading. It was to a large extent on these points that Newton based his summary, that "the aperture of ye instrument will be but small, ye object darke & confused, & also difficult to be found."

When Oldenburg had received Newton's comments and appreciated that Cassegrain's claim had been quashed, he wrote to Huygens to ask his opinion in the light of what Gregory had published.(7) Newton's letter was printed in the May 20 issue of the Philosophical Transactions immediately after the description from the offending Mémoire of what Oldenburg termed "the Cata drioptrical Telescope, pretended to be improv'd and refined by M. Cassegrain."(8) When Huygens saw this he wrote:

> "Mr. Newton treats him more gently than he deserves in my opinion, because aside from the fact that it is not his invention, it is rash to seek to outdo the proven inventions of others with ones which are not proven." (9)

Huygens' own review had appeared in the Journal des Scavans shortly afterwards, and in it he bluntly stated that Gregory had been the inventor, and pointed to the difference between the two designs being that Cassegrain did not specify that the mirrors should be conic sections, and that he had eliminated the eyepiece tube.(10) In his discussion of the instrument Huygens showed a surer grasp of practical optics than had Newton. Although there was a reason for conic sections, Huygens implied that these were not essential and indeed stated that it was less necessary that the secondary be a conic section: Cassegrain however could not expect the aperture to be greater without using a parabolic primary. The use of an eye tube was an "absolute necessity" to shield the eyepiece from all but the focused light - without it the observer would be dazzled. Huygens objected to the unsupported claim that some reflections were more natural than others, insisting that all were equally natural whether in or out of the axis. Thus, the supposed advantages were not advantages at all, and if "the essay of this telescope was made one could see how much this is distant from the truth". To the three telescope designs now published, Huygens added a fourth. Admitting that a flat mirror was preferable "because others are difficult to place and because they should be conic sections", he proposed that Gregory's secondary be replaced by a flat mirror, which would then be as large as half the diameter of the primary and intercept a quarter of the light.

Gregory's comments on Newton's telescope after he had read the accounts of it in the <u>Philosophical Transactions</u> were that the closeness of Newton's secondary to the eyepiece was preferable to the larger distance in Gregory's instrument, but its obliquity seemed a disadvantage. On the other hand his own telescope had "one disadvantage also verie considerable" which was that as both the concave secondary and the eye lens were movable the magnification was variable.(11)

Gregory received the printed description and criticism of Cassegrain's telescope from John Collins only in September 1672. Finding the instrument to be so close to his own, he felt "obliged to answer to these disadvantages Mr Newton finds in it".(12) Presumably Collins had described Huygens' review and the fourth form of telescope propounded there, because Gregory noted that by using this form "almost the whole disadvantages evanish" except only that the secondary was not as close to the eyelens as in Newton's design, but there were considerable advantages to counteract this. In spite of Newton's objections he felt that concave and convex secondaries might still be worth trying since they allowed the magnification to be changed.

Collins passed Gregory's letter to Newton, beginning a debate which extended over several months and ranged over a number of optical topics, concentrating nonetheless on Newton's defence of his reflecting telescope design. Newton clearly considered that Gregory's comments undermined the position he had adopted on the merits of the various telescopes (or rather the merits only of his own), and he replied at length and with great care and courtesy "because Mr Gregory's discours looks as if intended for the Press".(13) He admitted the attraction of the instrument with the flat secondary, but still preferred his own inclined secondary, principally because of his belief in the greater efficiency of oblique reflection.

Dismissing Gregory's somewhat crude analogy of a ball thrown against a wall, showing greater angular dispersion when thrown obliquely, Newton advanced his own theory of reflection. For Newton, reflection was not due to the solid face of a body but to two media whose interface was at the surface of the body. His analogy was of a stone reflected more readily from a surface of water if thrown glancingly, and its demonstration for light reflected from water was readily extended by Newton to light reflected from an "imperfectly polished plate" of metal. If the polished metal had reflected all the light incident on it there would, he claimed, have been no advantage in oblique reflection, but as it did not his method of inclining the mirror saved at least some light being lost.

His arguments for not using Gregory's flat mirror were largely irrelevant and did not amount to serious criticism. To counter Gregory's suggestion that it would halve the length of Newton's telescope, Newton could only imply a difficulty in grinding the flat mirror, and suggest that once the major hurdle of forming the primary had been passed "perhaps it may be thought most advantageous to make the best use of it though with a longer tube."

Whilst agreeing with Gregory that it would be an advantage to alter the magnification, he was pleased to realize that a proposal of his own had the same effect. The prismatic secondary that had been introduced to avoid Auzout's criticism that the metal of the mirror would tarnish, had also been proposed with convex faces. Although this was intended purely to erect the image, by altering its position it also allows the magnification to be varied and apparently with greater convenience than Gregory's solution.(14) To illustrate that there were a multitude of possible combinations of components (and also to imply that the best effect would be obtained with the fewest components) Newton suggested inserting a convex lens between the flat secondary of Gregory's proposal and the eyelens. Not only did this allow the flat mirror to be considerably reduced in size so that it obscured less of the primary, but it also erected the image and allowed the magnification to be varied.

Gregory in his reply in March 1673 generally admitted the force of Newton's arguments.(15) He broadened the discussion of reflection from an inclined mirror, suggesting that the scattering effect of the remaining scratches in the polished surface would make the reflection less regular, prompting a rather obscure reply from Newton which he could not understand. The remainder of the correspondence - Newton's letter of April and Gregory's reply of May 1673 - is taken up by a number of minor points, including a somewhat fruitless discussion of the effective magnification and field of view of Gregorian telescopes, with Newton still defending his original objection to this feature of Cassegrain's instrument.(16) The difference between them appeared to be the manner of limiting the eyepiece aperture to exclude scattered light. Gregory implied that Newton had been disingenuous in criticising Cassegrain on this count when Newton's own design for a reflecting microscope suffered from the same defect.

The correspondence came to an abrupt end; but it may have been concluded if, as he had intended, Gregory met Newton at Cambridge when he visited London in mid 1673 to acquire instruments for his observatory at St. Andrews.(17) This correspondence on the merits of the various optical schemes, and also on the nature of the trial of Gregory's telescope (discussed in an earlier section) reveals Newton as a cautious opportunist, anxious to lose not a single point, and ultimately successful in defending his instrument against Gregory's good-natured persistence.

Notes and References

1. Both possibilities are mentioned by Danjon & Couder (1935), 613 n41. Turnbull (1959), 152 n5 has favoured the former, and Bell (1922), 22 the latter. See Thoren (1971).
2. Denis (1672), 122: issue No.8, of 15 April 1672 (N.S.)
3. For a suggestion that the instrument was constructed in France about this time see Bell (1922), 23.
4. Turnbull (1959), 150-1: letter of Oldenburg to Newton, 2 May 1672.
5. The possible influence of the Optica Promota on Newton's is discussed in the section 'Newton's First Telescope'.
6. Turnbull (1959), 153-5: letter of Newton to Oldenburg, 4 May 1672.
7. Ibid, 155: letter of Oldenburg to Huygens, 6 May 1672.
8. Phil. Trans. R. Soc. Lond. 7 (1672), 4056-9: issue 83.
9. Hall & Hall (1973), 118: translation of letter of Huygens to Oldenburg, 21 June 1672.
10. Gallois (1672), 81-4: issue of 3 June 1672 (13 June N.S.).
11. Turnbull (1959), 228: letter of Gregory to Collins, 6 August 1672.
12. Ibid, 239: letter of Gregory to Collins, 23 September 1672. This reply to Collins' lost letter of 3 August was delayed until Gregory received a parcel of books, including issue 83 of the Philosophical Transactions.
13. Turnbull (1959), 248-52: letter of Newton to Collins, 10 December 1672.
14. This is discussed in the section 'Subsequent Work by Newton: Speculum Metal Telescopes'.
15. Turnbull (1959), 258-61: letter of Gregory to Collins, 7 March 1672/3.

16. Ibid, 269-71: letter of Newton to Collins, 9 April 1673;

    ibid, 278-9: letter of Gregory to Collins, 13 May 1673.

17. Whiteside (1972), 525.

3.8 MIRROR PRODUCTION BY NEWTON

In order to produce metallic mirrors Newton needed to find an alloy that was white, hard and malleable, that was not porous and that would take a fine polish. Latterly he appreciated that the stability of the surface was also important - the metal must not tarnish. Copper-tin alloys had long been known to be suitable for mirrors, and Newton consistently advocated a 3:1 ratio of copper to tin with additions of various other metals to improve its properties.

An early recipe from one of Newton's notebooks for "Metall for reflection" has already been quoted.(1) In this Newton has recommended the addition of white arsenic (the trioxide), tinglass (bismuth) to make it "tough", and regulus of antimony (metallic antimony) to make it "fine & of a steel colour". Nitre (potassium nitrate) and tartar (potassium hydrogen tartrate) were to be added as a flux to 'open the pores of the metal' and 'carry away the filth'. A.R. Hall has concluded that this dates from around 1665, and although this comes before Newton's early alchemical activity (from 1668-9) in which the properties of antimony played an important part, B.J.T. Dobbs has not suggested revising Hall's date.(2)

This composition and the procedure for casting it was essentially the same as that recommended by him in early 1672 after the submission of his second telescope. Three possible additives to basic copper-tin bellmetal were initially mentioned.(3) Tinglass made the metal white and reflective but tended to result in a casting which was full of tiny pores; arsenic made it white without making it porous; and antimony was likely to be a valuable additive. It is clear from a subsequent letter of Newton's that he believed a ternary alloy with arsenic as the only addition produced a satisfactory result; he was unsure as to the best proportions but warned that too much arsenic would make the alloy brittle.(4) It then transpired that the metal of the instrument sent to London had had silver as the third component: this had increased its reflectance but made it soft, and its susceptibility to tarnish proved a worry to Newton when the instrument came under criticism.

A variant method is given in a manuscript reproduced by Turnbull, and dated by him from the handwriting only to 1665-72, and apparently previously used by Brewster.(5) In a group of notes added to the main recipe (which is closely similar to the others discussed) Newton observed that some mirrors were recast by just melting the alloy, so as not to generate pores: this was the method subsequently hit upon by John Mudge to eliminate pores from the alloy, but Newton does not appear to have been aware of the advantage of recasting.(6) Another note described a method of purifying the copper by first melting it with some arsenic and crude antimony (stibnite) and adding quantities of nitre, subsequently removing the slag. This alloy was then mixed with the tin and additional arsenic as before. The effect however will have been to lower the melting point of the copper and so reduce the porosity of the eventual mix. A final alloy conjectured to have "greater powers of reflexion and ... more resistant to corrosion" would be obtained by omitting the additional arsenic and adding instead iron pyrites (?) and antimony.

A further recipe was given by Henry Oldenburg to Martin Lister in early 1674: this was to be sent to Francis Jessop of Sheffield who had apparently asked Oldenburg for "an account of ye Mettals compounding our speculums for reflecting light etc.".(7) The composition of 4lbs of copper, 1 of tin and $\frac{1}{8}$ each of antimony and arsenic, differs from other descriptions of speculum metal in having such a high proportion of copper. Oldenburg went on to propose suitable polishing agents, and his rejection of putty (tin oxide) suggests that he had consulted Newton's letters of January 1672. These were the letters in which Newton also discussed speculum alloys, so it may be that Oldenburg merely made an error in writing 4 for 3lbs: the comments are otherwise compatible with Newton's suggestions. The composition does not appear to be that used by Christopher Cock for the Society's 4 foot instrument.(8) Another composition was known to "a friend" of Oldenburg's, who at this period might well have been Robert Hooke.(9) Oldenburg suspected this alloy would be better than the other, "knowing ye curiosity and skill of ye possessor", and he thought he might be able to obtain it providing Jessop would promise that "it shall be kept privat." However there is no further mention of it.

The method of founding metal mirrors was not described in Newton's <u>Opticks</u>, presumably because the early telescopes now played only an historical role and progress was seen to lie with glass mirrors. However he did describe his method of grinding and polishing metal mirrors and controlling their curvature; but this procedure was applicable to glass also.(10) The main purpose of this seems to have been to publicise the advantages of polishing on pitch, a technique which Newton had been keen to describe to Hooke, but which was not widely practised.(11) Two copper tools were used, one to the required concave curvature of the mirror and the other convex, and both of 6" diameter for forming mirrors of 2" diameter. These had presumably been turned on a lathe to match gauges but this is not described. The mirror was then ground (presumably with a suitable abrasive such as sand) on the convex "till it had taken the Figure of the convex and was ready for a Polish."

> "Then I pitched over the convex very thinly, by dropping melted Pitch upon it, and warming it to keep the pitch soft, whilst I ground it with the concave Copper wetted to make it spread evenly all over the convex. Thus by working it well I made it as thin as a Groat, and after the convex was cold I ground it again to give it as true a Figure as I could. Then I took Putty which I had made very fine by washing it from all its grosser Particles, and laying a little of this upon the Pitch, I ground it upon the Pitch with the concave Copper till it had done making a noise; and then upon the Pitch I ground the Object-Metal with a brisk Motion, for about two or three Minutes of time, leaning hard upon it. Then I put fresh Putty upon the Pitch, and ground it again till it had done making a noise, and afterwards ground the Object Metal upon it as before. And this Work I repeated till the Metal was polished, grinding it the last time with all my strength for a good while together, and frequently breathing upon the Pitch, to keep it moist without laying on any more fresh Putty. ... I had two of these Metals, and when I had polished them both, I tried which was best, and ground the other again, to see if I could make it better than that which I kept. And thus by many Trials I learnt the way of polishing ..."

The purpose of the grinding of the fresh putty on the pitch with the tool was to embed the abrasive particles, because otherwise "they would by rolling up and down grate and fret the Object Metal and fill it full of little holes."

Newton used a microscope to examine the polished surface of the metal for "small pores onely discoverable by a Microscope" and alloys with this defect were rejected.(12) In this manner he also inspected the quality of the polish and noted the residual scratches:

> "in the best polish I have yet met with I find multitudes of long scratches as small as scarcely to be discovered without a Microscope, ... also for ye most part many deep though very small pits dug as it were in ye metall by ye sharp angles of ye corpuscles of Putty and other polishing pouders. And in these scratches & pits seems to consist the greatest imperfection of a good polish." (13)

In the grinding of both glass and metal, Newton stressed that care should be taken that the workpiece did not flex as this would certainly prevent a spherical figure from being obtained. Metal mirrors had to be cast thick enough, but for the thin meniscus shape of his glass mirror it was important to avoid pressing the glass too hard in grinding.[14]

Once polished, such glasses had to have a reflecting coat applied to the rear surface. The techniques for 'silvering' mirrors were well established by the time Newton's experiments were carried out in c.1682. By 1623 Sir Robert Mansell was already employing 500 men in "making, grinding, polishing and foyling looking glasses" in London; and although there was some interruption to the trade during the Commonwealth, the Company of Glass-sellers was incorporated in London in 1664 and a number of glass houses manufacturing mirror glass were established, including the Duke of Buckingham's famous works at Vauxhall.[15]

The process for flat mirrors involved the careful spreading of tin foil on a flat surface, rubbing mercury on its surface to form an amalgam, covering it with a layer of mercury and floating the polished glass over the tin. The glass was then pressed down on to the tin as the mercury was gradually drained off. Having remained weighted down for a day the glass was inclined to allow the drainage to complete and the film to harden. The procedure for coating a convex surface, as described in the 19th century, involved making a plaster cast in which the foil was spread; and once the glass had been pressed down on the mercury the glass and mould were inverted to allow the mercury to drain and weights were applied to the mould.[16] Newton was actively engaged in experimenting with amalgams of mercury in the early 1670s, and from his comment about his glass mirror before the amalgam was applied it appears that he foiled it himself.[17]

Notes and References

1. Hall (1948), 244: reproduced here in the section 'Newton's First Telescope'.
2. Dobbs (1975), 99.
3. Turnbull (1959), 82: letter of Newton to Oldenburg, 18 January 1671/2.
4. Ibid, 84: letter of Newton to Oldenburg, 29 January 1671/2.
5. Ibid, 85, reproducing and translating a manuscript from the chemistry section of the Portsmouth Collection (U.L.C. MS Add. 3973). Brewster (1855) II, 535.
6. Mudge (1777), 301.
7. Hall & Hall (1975), 480-1: letter of Oldenburg to Lister, 14 February 1673/4.
8. Turnbull (1959), 219: letter of Oldenburg to Newton, 16 July 1672. See the section 'Telescopes by Robert Hooke and Christopher Cock'.
9. Hall & Hall (1975), xxvi.
10. Newton (1704) I, 76-7.
11. Robinson & Adams (1935), entry for 18 February 1674/5.
12. See above, ref (3).
13. Turnbull (1959), 272 n3: unused portion of the draft of Newton's letter to Collins for Gregory of 9 April 1673.
14. Newton (1704) I, 77-8.
15. Powell (1923), 34, 37.
16. Ure's Dictionary, consulted in the 7th (1875) edition.
17. Dobbs (1975), 164; Newton (1704) I, 78.

3.9 TELESCOPES BY ROBERT HOOKE AND CHRISTOPHER COCK

The appearance of Newton's second reflecting telescope in London in late 1671 naturally stimulated speculation about its potential. The person most closely concerned with attempts to realise this potential was Robert Hooke, both because the Society automatically turned to its inventive Curator of Experiments to undertake any experimental work of this type required, and because Hooke's considerable previous experience in practical optics gave him strong personal reasons for wishing to make such improvements.

The circumstances surrounding the start of the Royal Society's telescope endeavours have already been described in the section devoted to the reaction to Newton's telescope. It is not clear on what basis the project was begun. Hooke presumably believed he could improve on Newton's small instrument and produce one of more useful dimensions; no doubt Brouncker was anxious to let him do so, and was probably prepared to leave the initiative and direction entirely with Hooke. The first task was to develop a suitable alloy for the mirrors, and at the first meeting of the Society after the Christmas recess he was able to announce "that he did endeavour to make such a Telescope himself, and to find out a Metall not obnoxious to tarnishing."[1] He had apparently already turned for the construction of the instrument, and probably also for the casting of experimental alloys, to his close associate Christopher Cock, who at the time was regarded as the leading London optical worker. The arrangement at this stage may however still have been a relatively informal one between Hooke and Cock. Although John Collins later mentioned that the Society had instructed Cock to make the instrument[2], this is not seen in the minutes, and his name is not at first associated with it. There may be a parallel with an arrangement of a few years later when an instrument developed by Cock for Hooke was subsequently purchased by the Society:

> "Mr HOOKE then produced a new microscope made after his directions by Mr CHRISTOPHER COCK, whereby the objects were exceedingly magnified ...
> the microscope was ordered to be bought of Mr COCK for the Society's use." (3)

Presumably the Society would not expect to make payment for the telescope until it performed to their satisfaction. However, it is clear that Cock found great difficulty in his attempts to meet the Society's (and Hooke's) exacting standards, and a reluctance to devote his time to an increasingly unrewarding commercial venture may perhaps explain the considerable delays and possible lapse of the work.

Cock had become free of a Guild Company before 1660 and may initially have been associated with the celebrated optician Richard Reeves, who had also enjoyed Hooke's patronage.(4) Cock worked for the Royal Society through Hooke's influence on numerous occasions, and had for example supplied the Society's 'Great Microscope' in 1669.(5) Occasionally he was present at meetings also, to discuss optical proposals such as the 6 foot diameter burning glass mooted in 1671.(6) His reputation was enhanced by the reception of microscopes and a long telescope which Oldenburg ordered for Hevelius in 1670 and 1671, and his work was highly recommended to Leibnitz.(7)

Hooke's manuscript diary is unfortunately not available for the period before August 1672, so we cannot be sure of the extent to which the work may have been shared between the two men. The indications however from the minutes of the Society's meetings are that Cock was responsible for all aspects of the construction, working under Hooke's direction. This contrasts with the position over a later instrument which was clearly Hooke's responsibility and for which Cock was contracted to provide unfinished parts.

The telescope first appeared, with Cock also in attendance, at the Society's meeting of 25 January 1672:

> "There was produced a Reflecting Telescope of four foot long after Mr Newton's way; which tho' the Metalline Concave was not duely polished, did yet pretty well, but was under-charged." (8)

John Collins prepared an account of the instrument for James Gregory not long after this meeting:

> " ... the Royall Societie ... gave Mr Cox order to make one after the same manner of contrivance [as Newton's] 4 foote long the which hath been done: one end of the Tube is open, at the other end is placed a Concave Metalline Mirrour the diameter whereof is betwixt 4 and 5 Inches, it was ground on a sphaere of 14 foote Diameter and about its focus which is about 4 foote off is placed a reflecting Plate as bigg as a two pence [about 5/8"] inclined at an Angle of 45 degrees to the Axis, so that the Reflected Rayes falling thereon, are againe reflected upright to the side of the Tellescope, where the Eye through a small hole wherein is placed a small Plano-Convex glasse beholds the object on the reflecting Plate, as much magnified as it could have been done by an ordinary Tellescope of 40 foote long or more, and void of colours: the Mirrour and Reflecting Plate are made to be taken out and wiped at pleasure ..." (9)

The references from the Society's minutes are confusing and have led the Halls to conclude that Cock made two separate instruments.[(10)] Indeed, one can readily interpret the published references as relating to as many as three instruments. The situation has not been helped by the fact that Birch failed to extract two relevant references in his printed version of the minutes. The telescope was produced again at the Society's meeting a week later. It was now "better than [at] the last meeting", and Hooke was recommended "to see it perfected as far as tis capable to do".[(11)] Whether this was done or not is not known. No telescope by Cock was produced at any subsequent meeting nor was an account given to the Society of its performance. Instead, at the following meeting on 8 February Cock was again present (having brought in a stone which he had polished and which the Society had previously thought would be suitable for making telescope mirrors) and he was "exhorted to perfect the Telescope of six foot of Mr Newtons way, which had been recommended to him".(12) Three references over the next few weeks are all to a six foot telescope and do not indicate that any progress was made. Then in mid-March Cock was present yet again at a meeting:

> "Mr Cock was ordered to make for the use of the Society, a Telescope of Mr Newton's way, of the length of four or five foot; which he promised to have ready in a fortnight's time." (13)

Subsequent references are all to a four foot telescope, and a description of this was provided by Cock for Oldenburg in July:

> " ... the object-speculum (being a compound of copper, tin, tin-glasse, antimony and a little arsenick) is of about 6 inches diameter, wrought upon a tool of about 14 or 15 foot [spherical diameter], and drawing [i.e. with a focal length of] 4 foot, more or lesse. ... Tis lodged in a square box, with a lid at the end of it, for placing the speculum-plate, lodged in it, at such a distance as shall be requisite". (14)

Are we then to conclude that there were three separate instruments of 4', 6' and then 4' focal length? There does seem to be a difference between the diameters of the main mirrors in the accounts given by Collins and Cock, and so we are probably justified in claiming that different mirrors were being described.(15) It may also be significant that the complex speculum alloy given by Cock contains all the components mentioned in Newton's letter of mid-January 1672 which was intended to guide the Society in its choice of alloy. In his letter however Newton was not proposing a five-component alloy, but three possible ternary alloys all based on bell metal.(16) Although it is possible that Hooke had independently arrived at this complex composition, it is more plausible that Cock had been asked to follow Newton's advice and had used an alloy that combined his various proposals. Newton's letter was read at the meeting when Cock first produced the telescope and when there was discussion about reflecting surfaces. As a result of this Oldenburg wrote to Newton to ask about the proportional composition of the arsenic alloy which was claimed to be without microscopic pores.(17) This may well indicate that the Society intended to try the alloy, and perhaps even that the presence of such pores had proved a problem with Cock's speculum. Newton's reply was read at the 1 February meeting, and agreement then to encourage Cock to try this new and hopeful alloy might explain the reference to a six foot telescope which "had been recommended" to Cock.(18) There is however no indication of a six foot mirror actually being made, merely a rising tone of impatience at the meetings in the apparent lack of progress.

If Cock was indeed developing a suitable alloy then these trials would take some time, and there may have been difficulties if we may judge from an early March letter of Oldenburg's in which he claimed that their hopes for the telescope would be realised "if only a metal can be made so compact and solid that it will reflect the rays as it should".(20) Moreover, if Cock was to make a mirror of a larger diameter and focal length he would have to form new moulds and grinding tools. The fact that the Society reverted so soon afterwards to a request for a '4 or 5 foot' telescope suggests strongly to me that Cock had not yet had these tools constructed. Possibly such trials as he may have made used the existing tools for the 4 foot mirror.(21) In any case, I would suggest that the 6 foot instrument never had a distinct existence and should be discounted. The

Society's move in mid-March to call Cock in and place an order for a '4 or 5 foot' telescope can be seen then as an act of exasperation rather than merely the placing of a repeat order.[22]

The instrument that emerged from this phase of activity was clearly the telescope described by Cock in July, and if we may believe the comments of Collins and Cock himself, he was now achieving some success. John Flamsteed, replying to a letter from Collins of 12 April, wrote that he was "glad to hear that Mr Newton's telescopes are made so well, as you intimate, by Mr.Cox", and asked Collins for information about their cost as he hoped to purchase one of 2'6" focus.[23] Cock later described the mirror to Oldenburg as being "a very good metal, shewing the moon very well, but other objects faint".[24] However there was clearly some difference of opinion about whether the instrument was ever in fact completed. Oldenburg wrote to Newton on 9 April and mentioned Cock's telescope "wch we long to see finisht, yt we may try its performances".[25] There was no further mention of the telescope in the minutes until the Society rose for its summer recess on 10 July. It was then proposed that some of the Fellows should continue to meet to prosecute various matters, including the improvement of telescopes "and particularly to see finished a four foot Telescope ... already recommended to Mr. Coxe."[26] Yet a few days later it was claimed on Cock's behalf that the telescope had "beene ready a pretty while".[27] After the recess Hooke was called upon to describe the trials that had been made over the Summer, but no mention was made either then or subsequently of Cock's telescope: instead Hooke was full of plans for a more ambitious instrument.[28] There are no entries in Hooke's diary that can be connected with the instrument with any degree of confidence.[29] It does not appear to have been retained by the Society as it does not figure in Nehemiah Grew's 1681 catalogue of the Society's collections.[30]

Newton wrote to Oldenburg shortly after the recess had begun asking whether Cock could make him a four foot telescope, leaving only the polishing of the mirror for Newton to complete, and Cock offered to sell for £5 the very instrument that he had been making for the Society.[31] The telescope was still apparently Cock's property, and so presumably he saw little prospect of it being fully acceptable to the Society and was attempting to recoup what he could. The fact that the offer was made through Oldenburg suggests that the telescope had become something of an embarrassment and that Oldenburg was happy to find that it might be of interest to Newton. The possibility that Newton received the instrument is discussed in the following section.

Cock's difficulties appear to have been principally with the casting, figuring and polishing of the primary mirror, and not with the structure of the telescope. Bearing in mind the continued use of 4 foot focal length mirrors and assuming that the earliest mirror had been abandoned as unsatisfactory it would be natural for the replacement mirror to have been fitted in the same telescope. There is also some indication that the structure was adaptable, since when Cock polished a steel speculum for the Society, of only 3" diameter but unknown focal length, this was "to be used in the reflecting telescope".[32] The earlier and later accounts both apparently describe removable mirror cells, and so possibly the cell was adapted from time to time to accept mirrors of different diameter. It is proposed then that Cock made only two telescopes, but that these were in effect the same instrument, merely appearing in different guises having been fitted with at least two specula of the same focal length.

The steel speculum was made from one of several experimental materials for possible use as mirrors which were tested by Cock. At the meeting when the 4 foot telescope was first produced Sir Robert Moray "shewed the Company a small piece of Opaque Glass, made by Mr Boyle, to serve for Reflecting Concaves", but although Boyle was to be asked if a larger piece could be made there was no further mention of it. Later in the same meeting however Dr. Edward Browne produced

> "a remarkable kind of fine black stone, sent to his father Sir Thomas Brown, out of Iceland, seeming to agree with the Lapis Obsidianus described by Pliny ... It was delivered to Christopher Cock the Perspective-maker, to try, whether it would be fit for reflecting Concaves ..." (33)

Cock brought the obsidian back two weeks later and the vitreous lava was seen to have taken a good enough polish for it to be deemed "very fit for making such reflecting Speculums as are requisite for Mr Newtons new Telescopes", but further trials would have to await the arrival of more pieces.(34) The use of steel as a speculum metal was probably first discussed with Cock at the Society's 14 March meeting, and must have been reported to Newton who expressed the hope that "the steely matter imployed at London be more strongly reflective" than the metal he had used.(35) About a month later the speculum was shown to the Society: Cock had been unable to make it "all over of one and the same hue, it being in its greater part darker than in the rest about the Edges", but the Society rather than risk further delay instructed him "to polish it as it was".(36) Another month went by before it was handed over, and Hooke still claimed that it was "falsely polished."[37] The most likely reason for Cock's difficulty was that the disc had been forged so that its crystalline structure would not be homogeneous and there would be residual internal stress. Cock gave a brief account of it for Newton in July 1672:

> " ... tis a pure Venice-steel, forged with much Care; not melted, nor compounded with any thing; of 3 inches diameter, but bearing not so good a polish ... tis very hard & tedious to grind this steely matter true." (38)

Hooke's activities in this period are far from certain. Although he was clearly directing Cock's work on the 4 foot telescope he may have played little part in its actual construction. The only item which may have been directed to him personally was the testing of prismatic secondary mirrors, but there is no indication that this was pursued.[39] It would be surprising however if he was not involved in some independent experiments, and isolated references in Flamsteed's correspondence suggest that he may have been active.[40] Similarly, in July 1672 he reported he had "made a Refracting object-glass upon the same sphere with a Reflecting one" and found that he obtained a brighter image with the former, using the same magnification and aperture.[41] From August 1672 a manuscript diary of Hooke's is available, and in this there are numerous if somewhat cryptic references to telescope projects. Something that emerges clearly from this is the close working relationship between Hooke and Cock: they were constantly meeting to discuss practical matters and optical commissions, they lent each other tools, and Cock arranged for the casting of specula and undertook preliminary grinding. Many of the telescope references are difficult to interpret: hence for example "Polisht an object speculum of 7 inches" was probably a 7" focal length mirror, but might be a 7" diameter mirror of much longer focal length.[42] Possibly by now Cock was producing a few small reflectors commercially, for in August 1672 Hooke noted "[at] Coxes, a little concave", and in January 1673 "Cox shewd Scroter [William Schroter, FRS] Reflex-telescope mended by himself for [?Sir Andrew] King."[43] It would be of great interest to know more of the early August entries "Gave Lord Brounker Reflex Speculum" and "Fitted my Newton" since these may refer to relatively small instruments by Hooke.[44]

By mid-August 1672 Hooke had embarked on a more ambitious project - the construction of a 9 foot focus instrument. Cock supplied the speculum, and Hooke established a special work room in the cloister at Gresham.[45] His carpenter, the aptly named Coffin, made the telescope structure, or "specular frame", and on August 18th Hooke "Tryd speculum hopefully".[46] On the 23rd we find "Pollish 9 foot speculum well. Saw Moon at night through it very big and distinct", whereas on September 1st he "observed Mars with speculum, but not so good".[47] Presumably this 9 foot focus speculum had a comparatively small diameter because when Hooke presented a progress report to the Society when meetings were resumed at the end of October:

> "Mr Hooke said that hitherto he had wanted a Mould of a sufficient bigness for a Speculum, designed by him, of 15 Inches Diameter, for a Tube of ten foot long; But that he hoped to have in a week or fortnight such a Mould cast wherein a Speculum of that bigness might be well wrought and polished." (48)

The mould described here is not a mould for the casting of the concave speculum itself, but is the convex tool on which the speculum was ground and polished. It is not clear whether the 15 inch diameter refers to the speculum or to the tool, which would necessarily be rather larger than the speculum. Certainly by following Newton's table of recommended apertures, and scaling up from his proposed diameter for a 4 foot focus speculum, one obtains 9 to 11 inches as the diameter for a 9 foot mirror.(49) If Hooke was following Newton's further suggestions of making the mirrors oversized so that the outer zones could be masked off, then (again scaling up from the proposal made for the 4 foot instrument) the speculum would be around 14 inches across. However, in view of the experience of Hooke and Cock with the figuring of earlier large specula, which had comparatively small ratios of diameter to focal length, I think this may safely be discounted, and it may be supposed that this instrument had a speculum of around 10 inches diameter.

Cock agreed to have the tool cast and then apparently hired it to Hooke for 50/-.(50) It was delivered to Hooke on 19 November, and the next day he was able to report to the Society that "the great Tool for grinding the Reflecting-glass was now ready", and the following week that "he had tryed the said tool so far as to find it pretty just."(51) Grinding trials began, but problems must have arisen as the tool was back with Cock in December, and then at the end of the month: "Cox here, he told me of metall warping which I found true".(52) Aside from problems with the casting, the composition of the alloy appeared to be at fault as Collins recounted:

> "Cox the Glasse grinder thinkes that neither his [Hooke's] Devices nor this new Tellescope will obtaine repute in the World, the mettall suddainly tarnishing." (53)

Hooke's illness at this time, and presumably also the need to cast a new mirror, delayed the work. When grinding began again Hooke was helped by the young Henry Hunt who had joined him as his assistant a few days before. Only a few clues are given as to Hooke's techniques, but we find that initial grinding was being performed with a "Lead mallet", and "washt sand" was sold to him by Cock towards the end of the grinding and before polishing began.(54)

The work went well. On 18 January Hooke tested the speculum and found it "almost true".(55) At the Society's meeting:

> "Mr Hook produced an Essay of a Reflecting Objective Speculum, being the Segment of a Sphere of thirty six foot [i.e. of 9 foot focus], which he hoped when perfectly polished, would perform as much as a Refracting object Glass for 100 foot Tube. He was sollicited to see it brought to perfection." (56)

The figure and polish were improved progressively over the next few days. Working with Hunt he "polisht it pretty trew, but not perfectly having a cloud in the middle about the bignesse of 3 inches over", but later he noted he had "cleerd Specular metall which Sir R. Moray saw", and the mirror "upon tryall [was] found good".(57) The Speculum was taken to the Society's next meeting, and although his report was hopeful, he pessimistically recorded in his diary "carryd Speculum to Arundell house, not good".(58) Trials over succeeding days were all "not good" or "succeeded not", until on 20 February:

> "In the morn made the last tryall with Speculum it succeeded well by roughing the tool and cleansing it. it was true in the middle and on one side." (59)

After this "Cox had home his tool" and the telescope makes no further appearance in the diary, or to my knowledge elsewhere.

Another flurry of activity in August 1673 shows Hooke experimenting with a new technique. Gregory had written to Collins in March 1673 continuing the long debate with Newton over the relative merits of their reflecting telescope designs, and he had described the use as burning glasses of back-silvered glass mirrors instead of metal specula.(60) The letter was read at the Royal Society later in the month and it may have been this that prompted Hooke to experiment with glass mirrors in reflecting telescopes. The "new concave" was received from Cock on 11 August, and was worked on by Hooke and Cock amid some excitement on Hooke's part at his "new way of pollishing" which apparently made use of local polishers.(61) The first hint that this was a glass mirror comes with the entry for 19 August when Hooke "Ground Convex part of new glasse in the morn".(62) After the "great Labour" of polishing, the glass was tried and "though ill polisht I found it exceeding true".(63) Confirmation that it was a glass mirror is given in the entries "Sent to have it foyld" and "foyld new glasse" which refer to the application of the reflecting surface.(64) Whether this was successful or not is unknown as there are no further clear references to it in the diary.

It seems probable however that it was this telescope, or an immediate successor to it, that Hooke was referring to in January 1674 when he wrote that he had "Told him [Oldenburg] of New Reflex telescope".(65) A week later at the Society's meeting Hooke "Shewd the new telescope to see direct by Double reflection"(66), and from the account in the Society's minutes it is clear that the telescope was a Gregorian reflector:

> "Mr Hook produced a new kind of Reflecting Telescope of his own Contrivance, differing from that of Mr Newton in this, that the observer looked directly at the object erected. This was performed by a way propounded by Mersennus and is repeated in Mr Gregory's Optick; but is believed was never actually done before." (67)

An undated letter from Hooke to a titled recipient, assumed to be Lord Brouncker, was discovered by William Derham amongst Hooke's papers and almost certainly relates to this telescope:

> "I have lately made a telescope by reflection, with which I look directly at the object, and see it very distinct, and magnified. And this by planting a small <u>lens</u> in the middle of the <u>object speculum</u>, and planting another small <u>concave speculum</u>, beyond the focus of the <u>object speculum</u>; the manner of which your Lordship will readily understand by the annexed scheme; where <u>ab</u> represents the object speculum, <u>e</u> the focus of that speculum, <u>fg</u> a small concave speculum, serving to reflect the rays to a second focus <u>d</u>, where the eye <u>k</u> see the

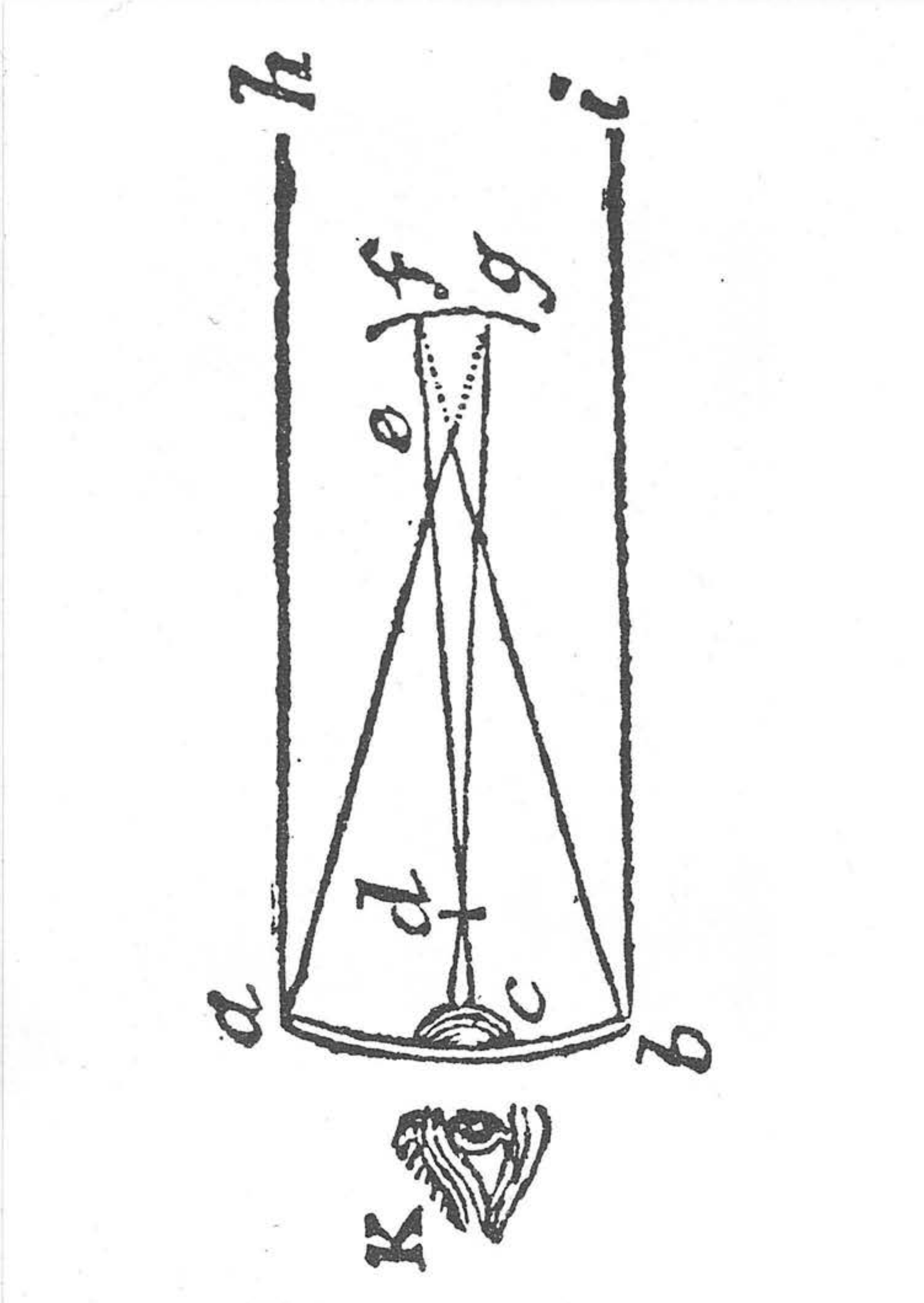

Fig.5. Robert Hooke's Gregorian reflecting telescope of 1673-4, from an unlocated letter by Hooke published by Derham in 1726.

> object by the help of the small lens c. 'Tis easy to contrive the cell for the eye, that the rays that pass on each side of fg shall not disturb vision." (68)

The diagram shows the eyelens "planted" on the inner surface of the primary mirror, which is not perforated at the centre as a metal speculum would have to be. This may then be a further indication that this depicts a glass mirror, since the mirror could be effectively perforated if the reflecting amalgam was cleaned off the centre portion of the glass. Although this would not be particularly satisfactory, particularly if the eyeglass was small, it would nevertheless demonstrate the principle of the instrument.

Hooke continued to exploit the properties of reflection in his telescopes. In 1667 he had experimented with reducing the length of a refracting telescope by using a number of opposing plane mirrors to 'fold up' the light path so that the light leaving the object glass was reflected up and down a short tube before coming to a focus.(69) From this developed Hooke's 'Helioscope' in which the low reflectivity of some imaging surfaces was put to good effect by reducing the intensity of the sun's image, allowing it to be viewed in a telescope.(70) In January 1675 Hooke read "a Lecture about Helioscopes and shortening tubes" to the Royal Society.(71) Over the next few months several helioscopes were constructed and demonstrated at the Society's meetings, and in October 1675 his pamphlet A Description of Helioscopes was published as his third Cutlerian Lecture.(72)

The objectives of these instruments could be either "refracting or reflecting Spherical Glasses" depending on the characteristics of the image required, and in the plate accompanying the pamphlet eight of the many possible optical arrangements of lenses and mirrors were shown.(73) For viewing the sun, in other words for using these instruments as helioscopes, it was recommended that the plane and spherical mirrors be made of black glass.(74) However, other reflecting surfaces are also described, making it clear that the designs are seen as a more general method of shortening telescopes. Metal alloys of tin, copper, iron, antimony and arsenick had been tried, but although they had been brought to "a very glaring polish" they had proved "spongy" or porous.(75) Glass quicksilvered on the reverse had given the best reflection but the image had been confused by reflection at the upper surface of the glass. With great ingenuity Hooke had solved this problem by making these mirrors as thin wedges, so that the reflection from the upper surface was thrown to one side, and then opposing two wedges to reduce the resultant chromatic effect.(76) Such mirrors were of use in shortening telescopes "for the <u>Moon</u>, <u>Planets</u>, and other Objects", but

> "Not at all to our present purpose of making a <u>Helioscope</u>, where we make use only of the reflection of the first superficies of the Glass, and where our main aim and design, is, the loss of the strength and brightness of the Rays, and not for preserving the strength and brightness of the Rays, or augmenting them." (77)

The only design proposed by Hooke for a telescope with a reflecting objective (fig. 7 of his plate) was certainly a helioscope with a black glass mirror, but he does appear to have developed a further type of reflecting telescope specifically for observing the moon. One of Hooke's schemes was the establishment of a select club within the Royal Society, but free from Oldenburg's influence.(78) When it first met in January 1676 as "our New Philosophicall Clubb", Hooke described this instrument:

> "Next I told them of my Selesnoscope which I had already made use of these 6 monthes, made by Reflection from the Superficies of glasse. I told them of one I had made of 50 foot focus. and of my making one of 30 f. I told them how strangely clear it represented All the parts of the Moon both those of the limb and those of the middle parts at all times and even in a full Moon Distinct." (79)

By referring back in Hooke's diary it is possible to follow the selenoscope's development, but not without some difficulty in interpretation. In July 1675, shortly after the construction of the two helioscopes shown at the Society's meetings, Hooke "bespoke concave for Helioscope" from Cock; three days later he "Tryd Glasse by Reflection", and after a further four days he "tryd the telescope on the Moon by the Reflection on the concave side of my 24 foot object glasse which drew 12 foot".(80) This cannot have been a conventional convex objective lens to which a reflecting foil or amalgam had been applied, since the focal length of such a lens/mirror combination would have been much shorter than 12 feet. On the assumption that this was not a dark glass, since the moon was one of the objects to be viewed by highly reflective materials, it is presumed that it would have been a concavo-convex lens coated on the reverse. However, this hardly fits the description of reflection on the concave side of the glass, nor does it satisfactorily explain why this instrument was especially designated as a lunar telescope and not merely as a reflecting telescope. The answer may perhaps lie in Hooke's later hint that if

> "the brightness and radiation of the <u>Moon</u>, <u>Venus</u> or <u>Jupiter</u>, do somewhat offend the eye, they will presently lose their beards and look very distinct, if one reflection from glass be made use of in the Telescope." (81)

Possibly then the selenoscope employed a dark glass concave as an objective. The optical arrangement must however have been different from the helioscope that used only reflecting surfaces. In the helioscope the light passed through a transparent glass plate before striking the main mirror, and the glass plate, which was slightly inclined, was used to reflect the light backwards in the tube, where it suffered further reflections before being brought to a focus. Possibly Hooke inclined the main mirror slightly so that the convergent beam was out of the path of the incoming light and so could be intercepted by a solid mirror rather than a transparent plate.

It is even conceivable that selenoscopes produced later in the year, and which appear to have had glass mirrors, had silvering applied to the front surface. Hooke mentioned in his dairy how at the end of July he had hit on a method of depositing silver:

> "by accidentally throwing away a solution of Silver I observed how it made ...
> Also that this silver powder did presently silver over brasse upon which it was Rubbd whence I judge it will be an excellent way for making Reflecting concave for telescopes or Burning." (82)

Whether Hooke pursued this is not known. Unfortunately the references to the various instruments are too fragmentary to allow the nature of the reflecting surfaces to be identified, and it must remain conjecture that the selenoscope used a dark glass concave.

During September and October there are several references in the diary to the grinding of concave glasses, and these follow his stated intention to make a telescope for the moon "by reflection from glasse".(83) In mid October he was working on a 25 foot reflecting glass and on the "frame for the Selenoscope". He also "Found Reflex glasse [to be] about 90 foot Radius", which corresponds well with his later claim to have a selenoscope of 50 foot focus: presumably the 25 foot glass was for the selenoscope later described as of 30 foot focus.(84) The instrument was fitted in the 'Turret' observatory over Hooke's lodging at Gresham College, and it performed well, for we read in mid November: "Used Selenoscope exceeding good".(85)

A further instrument produced in early 1676 is likely to have had a reflecting objective, since Hooke described having borrowed the "tool from Cox for 40 foot Reflex", but it may have had a refracting objective and used reflection only for the internal mirrors. Beyond the fact that with it he "saw Venus fair" the instrument is not described.(86)

On a number of occasions in this period there was discussion of abrasives and polishing materials, showing that both Hooke and Cock were actively experimenting. Thus in September 1675 Hooke "Discoused at Coxes ... of grinding glasse with brick Of polishing with paper and Tripoly", and later "At Coxes he told me the way of polishing with white marble tooles covered with thin paper and dusted with tripoly."(87) In December Hooke boasted to Aubrey of "my way of boyld alabaster Dust and Sand moved by filing", and it may have been this that induced Cock to promise "to grind me a glasse of any shap if I would shew him my new way."(88)

Although this effort appears to have been directed to working glass, speculum metal was not ignored. In February 1675 Newton had attended his first meeting of the Royal Society and had talked to Hooke afterwards and described "his way of polishing metall on pitch."(89) In July Hooke was discussing a new alloy which was claimed not to be brittle, and in December he arranged to obtain specula from Cock.(90)

In late 1679 the subject of metal alloys, and particularly of apparent discrepencies in the specific gravities of alloys of known components, was intensely investigated by Hooke for the Society. Between December 1679 and April 1680 scarcely a meeting went by without a detailed report from Hooke on the weighing of numerous components and alloys. In the course of this he made some experiments on the use of copper/tin alloys for reflecting specula, but unfortunately the proportions of these are not known:

> "Mr HOOKE gave an account of some other qualities which he had taken notice of in the mixture of tin and copper, as: 1. That the colour of copper was quite destroyed, it appearing much of the colour of iron, when polished ... 3. That it bore a pretty good polish and reflection ... 5. That viewing the polished surface of it with a glass, he found it very full of extremely small holes or blebs in the metal". (91)

A little later, an alloy of antimony, iron and tin in the ratio 1:1:2 was found to hold "a very good polish", and "We conceive it may be very useful for making speculative glasses for Mr NEWTON'S experiment."(92) Still thinking of telescope specula, Hooke proposed using a method of casting specula from an amalgam of mercury and iron, moulding them on the convex face of a large object glass. Hooke had not yet tried to harden the amalgam, which he claimed was done with a "vegetable powder", nor would he be successful in the attempt.(93)

Although Hooke continued to take an active interest in telescope construction, reflecting objectives now ceased to figure in his work. A further helioscope, now "perfected", but relying on an objective lens, was produced in 1681.(94) In the succeeding twenty years the availability of improved long focus objectives, notably the Society's 123 foot lens by Constantine Huygens, led Hooke to experiment with aerial or tubeless telescopes and he did not return to reflecting objectives.

Notes and References

1. Roy. Soc. MS Journal Book, meeting of 11 January 1671/2. This information was passed to Newton in a lost letter written shortly after the meeting.

2. Turnbull (1939), 222: undated comments by Collins probably made before 8 February 1671/2 and sent to Gregory on 23 February.

3. Birch (1756-7) III, 418: meeting of 27 June 1678.

4. Taylor (1954), 248; Turner (1966), 126; Hooke (1665), Preface E1^{v}. Reeves was a turner, rather than a spectacle-maker (Gunther (1930), 206); Cock may have been apprenticed in this company also, although he was admitted to the Spectacle-makers in 1680 (Court & von Rohr (1929-30), 74).

5. Gunther (1930), 348.

6. Birch (1756-7) II, 471.

7. Hall & Hall (1970), 47, 128, 467: letters of Hevelius to Oldenburg, 25 June, 17 August 1670, 22 February 1670/1; ibid, 280: letter of Oldenburg to Leibnitz, 28 September 1671.

8. Roy. Soc. MS Journal Book, meeting of 25 January 1671/2.

9. See above, ref (2).

10. Hall & Hall (1971), 537 n3.

11. Roy. Soc. MS Journal Book, meeting of 1 February 1671/2.

12. Ibid, meeting of 8 February 1671/2.

13. Ibid, meeting of 14 March 1671/2.

14. Turnbull (1959), 250: letter of Oldenburg to Newton, 16 July 1672.

15. It seems clear that Collins was referring to the physical and not the effective diameter of the mirror.

16. Turnbull (1959), 82: letter of Newton to Oldenburg, 18 January 1671/2.

17. Ibid, 83 n1: lost letter of Oldenburg to Newton, 27 January 1671/2, known from Oldenburg's notes. In this he repeated the points of his 20 January letter but also "desired ye proportions of arseneck and metal".

18. Newton's reply of 29 January 1671/2 recommended a proportion of only about 1/6 to 1/8 by weight of arsenic (ibid, 84), and Cock was careful to state in July that his alloy contained merely "a little arsenick" (ibid, 219).

19. Thus on 22 February: "The Curator was desired to press Mr Coxe to expedite" the telescope (Roy. Soc. MS Journal Book).

20. Hall & Hall (1971), 575: translation of letter of Oldenburg to Sluse, 4 March 1671/2.

21. An element of expediency in Cock's undertakings can be seen in incidents such as the supply in 1670 of a 50' focus objective to Hevelius when a 60' lens had been ordered: Hall & Hall (1970), 48: letter of Hevelius to Oldenburg, 25 June 1670.

22. On the same occasion the Society took the opportunity to remind Cock of the large burning speculum that had been discussed with him a year before. Although he agreed to contract with the founder, the project seems to have lapsed again.

23. Rigaud (1841) II, 136.

24. Turnbull (1959), 219: letter of Oldenburg to Newton, 16 July 1672. Cock attributed the faintness of the images to the magnification being too great.

25. Ibid, 135: letter of Oldenburg to Newton, 9 April 1672.

26. Roy. Soc. MS Journal Book, meeting of 10 July 1672.

27. Turnbull (1959), 219: letter of Oldenburg to Newton, 16 July 1672.

28. Roy. Soc. MS Journal Book, meeting of 30 October 1672.

29. Robinson & Adams (1935), entries from August 1672 only. The Halls suggest some entries are connected, but associate these with the earlier telescope: Hall & Hall (1971), 537 n3.

30. Grew (1681).

31. See above, ref (27).

32. Roy. Soc. MS Journal Book, meeting of 8 May 1672.

33. Ibid, meeting of 25 January 1671/2. The opaque glass made by Boyle may have been similar to a lead potash glass with which William Herschel experimented and from which a speculum now in the Science Museum, London, was constructed (Inv. 1925.462). The material was mixed as a paste and fused after figuring. See Turner (1977), 128 n81, and Steavenson (1924-5), 214,227.

34. Roy. Soc. MS Journal Book, meeting of 8 February 1671/2.

35. Turnbull (1959), 124: letter of Newton to Oldenburg, 26 March 1672. Oldenburg probably passed the information to Newton in his lost letter of 23 March. This was the only reference to the Society's telescope-making activities to appear in the Philosophical Transactions. The initial suggestion was presumably prompted by the use of steel for domestic looking-glasses before plate glass mirrors were manufactured in this country in the earlier part of the century: steel mirrors continued to be used after the Restoration (Edwards (1924-7) II, 313).

36. Roy. Soc. MS Journal Book, meeting of 18 April 1672.

37. Ibid, meeting of 8 May 1672.

38. See above, ref (27).

39. Roy. Soc. MS Journal Book, meeting of 4 April 1672: "Ordered, that ... the Curator take care to make such a Crystalline prism for the design [i.e. purpose] mentioned and to try the same." At a subsequent meeting Hooke proposed what was felt to be a

rather impractical method of "making these Reflecting Concaves in great numbers and polished by the means of two Dyes one concave and another convex, putting between them a Plate of Silver, and then stamping them with the Mint-mill": ibid, meeting of 18 April 1672. Although this was referred to Henry Slingsby, Warden of the Mint and a founder Fellow of the Society, no report was forthcoming.

40. Hall & Hall (1971), 580: letter of Flamsteed to Oldenburg, 8 March 1671/2. Rigaud (1841) II, 136, 153: letters of Flamsteed to Collins, 17 April & 10 July 1672.
41. Roy. Soc. MS Journal Book, meeting of 10 July 1672.
42. Robinson & Adams (1935), entry for 5 August 1672. King (1955), 77, has assumed this to be the diameter.
43. Robinson & Adams (1935), entries for 7 August 1672 and 10 January 1672/3.
44. Ibid, entries for 9 & 11 August 1672.
45. Ibid, entries for 11 & 16 August 1672.
46. Ibid, entries for 17, 18 & 24 August 1672.
47. Ibid, entries for 23 August and 1 September 1672.
48. Roy. Soc. MS Journal Book, meeting of 30 October 1672.
49. Phil. Trans. R. Soc. Lond. 7 (1672) 4033-4: Issue 82, dated 22 April 1672.
50. The figure was agreed on 4 November 1672. It is referred to always as Cock's tool, and finally on 20 February 1672/3 "Cox had home his tool". The cost of the cast speculum was £1, paid on 22 January. Robinson & Adams (1935).
51. Ibid, and Roy. Soc. MS Journal Book, meetings of 20 & 27 November 1672.

52. Robinson & Adams (1935), entry for 30 December 1672.

53. Turnbull (1939), 249: letter of Collins to Gregory, 26 December 1672.

54. Robinson & Adams (1935), entries for 15 & 26 January 1672/3.

55. Ibid.

56. Roy. Soc. MS Journal Book, meeting of 22 January 1672/3.

57. Robinson & Adams (1935), entries for 27 & 31 January, 1 February 1672/3.

58. Ibid, entry for 5 February 1672/3. At the meeting Hooke had "affirmed [the speculum] to be now true, tho' not perfectly polished. He said he would endeavour to give it due polish against the next Assembly". Roy. Soc. MS Journal Book.

59. Robinson & Adams (1935).

60. Turnbull (1959), 260: letter of Gregory to Collins, 7 March 1672/3. Read at the Royal Society on 26 March.

61. Robinson & Adams (1935), entries for 11-17 August 1673.

62. Ibid.

63. Ibid, entries for 22 & 23 August 1673.

64. Ibid, entry for 23 August 1673.

65. Ibid, entry for 29 January 1673/4.

66. Ibid, entry for 5 February 1673/4.

67. Roy. Soc. MS Journal Book, meeting of 5 February 1673/4.

68. Derham (1726), 269: Gunther (1930), 744. It is possible that the recipient was Lord Delamer with whom Hooke and Cock were discussing a telescope proposal in late December 1673.

69. In November 1666 Hooke was hinting of "optic-glasses upon new principles"; after a number of reminders he produced "a box with optic-glasses fitted in it, designed to contract the power

of a long telescope into a short one", in February 1667, and the instrument was still being discussed in June 1667: Gunther (1930), 286, 294, 306. Hooke subsequently recalled that the instrument had been shown in 1668: Hooke (1676), 4.

70. Hooke first made the suggestion of adapting the contracted telescope as a solar instrument in June 1667: "He intimated, that this sort of telescopes would serve for a very convenient helioscope, to look upon the sun at all time, when it shines, without offence to the eye": Gunther (1930), 306.

71. Robinson & Adams (1935), entry for 28 January 1674/5.

72. Optical components were obtained from Cock in January 1675, and the bill was paid by the Society in March. At the end of March he was working on a "New Helioscope" and this was exhibited in May; the instrument shown in June was apparently different. Ibid, entries for 24 January, 19 March 1674/5, 31 March 1675; Gunther (1930), 432, 434. The Description of Helioscopes is dated 1676 on the title page, but Hooke was distributing copies in October 1675: Robinson & Adams (1935), entries for 11, 12, 17, 18, 21, 28 October 1675.

73. Hooke (1676), 4, Plate I.

74. Ibid, 2. Other dark surfaces proposed were black marble and glass of antimony: ibid, 6.

75. Ibid, 5.

76. Idem.

77. Ibid, 6.

78. Gunther (1930), 435: letter of Hooke to Aubrey, 24 August 1675.

79. Robinson & Adams (1935), entry for 1 January 1675/6.

80. Ibid, entries for 5, 8, 12 July 1675.

81. Hooke (1676), 9.

82. Robinson & Adams (1935), entry for 31 July 1675.

83. Ibid, entries for 3 September 1675, etc. Some frustration with Cock, who was presumably doing preliminary grinding, was shown on 19 September when Hooke "Walked to Coxes, he had done nothing".

84. Ibid, entry for 18 October 1675.

85. Ibid, entry for 16 November 1675.

86. Ibid, entries for 4 February, 20 March 1675/6. This instrument is certainly distinct from the 40ft telescope proposed in March 1698: Waller (1705), xxv.

87. Robinson & Adams (1935), entries for 25, 29 September 1675.

88. Ibid, entry for 11 December 1675.

89. Ibid, entry for 18 February 1674/5.

90. Ibid, entries for 10 July, 17 December 1675.

91. Gunther (1930), 542: meeting of 5 February 1679/80.

92. Ibid, 551: meeting of 25 March 1680.

93. Ibid, 555: meeting of 13 May 1680.

94. Ibid, 577: meetings of 13, 27 July 1681.

3.10 SUBSEQUENT WORK BY NEWTON

3.10a Speculum Metal Telescopes

Although Newton's name is normally only associated with the small telescopes of 1668 and 1671, he continued to have an active interest both in the theoretical possibilities of reflecting telescopes and in the practical problems of their production. This interest took in three types of imaging objective - the familiar metal mirror, a compound lens with a reflecting surface, and finally a back-coated glass mirror. These will be treated below in turn.

Amongst the Newtonian manuscripts at the University Library, Cambridge, is a design in Newton's hand for a small reflecting telescope. The manuscript has been reproduced by Turnbull(1), and is in the form of a dimensioned perspective view of an instrument simply mounted on a circular base, together with an exploded view and description of the components at the objective end of the tube. Turnbull has dated it to 1671/2, but elsewhere infers an association with the 1668 telescope(2); more recently Mills and Turvey have proposed that the manuscript indeed represents Newton's first telescope.(3) Whiteside has also dated the manuscript to before the second telescope.(4) However, certain features of the design clearly indicate a later date, probably in the second half of 1672.

There is no definite evidence that such a telescope was ever constructed. Rather, the manuscript appears to show an idealised scheme for a small telescope, incorporating various improvements proposed by Newton after the submission of his second telescope to the Royal Society. Thus, for example, attention is concentrated on the construction of the tube, and Newton's interest has not extended

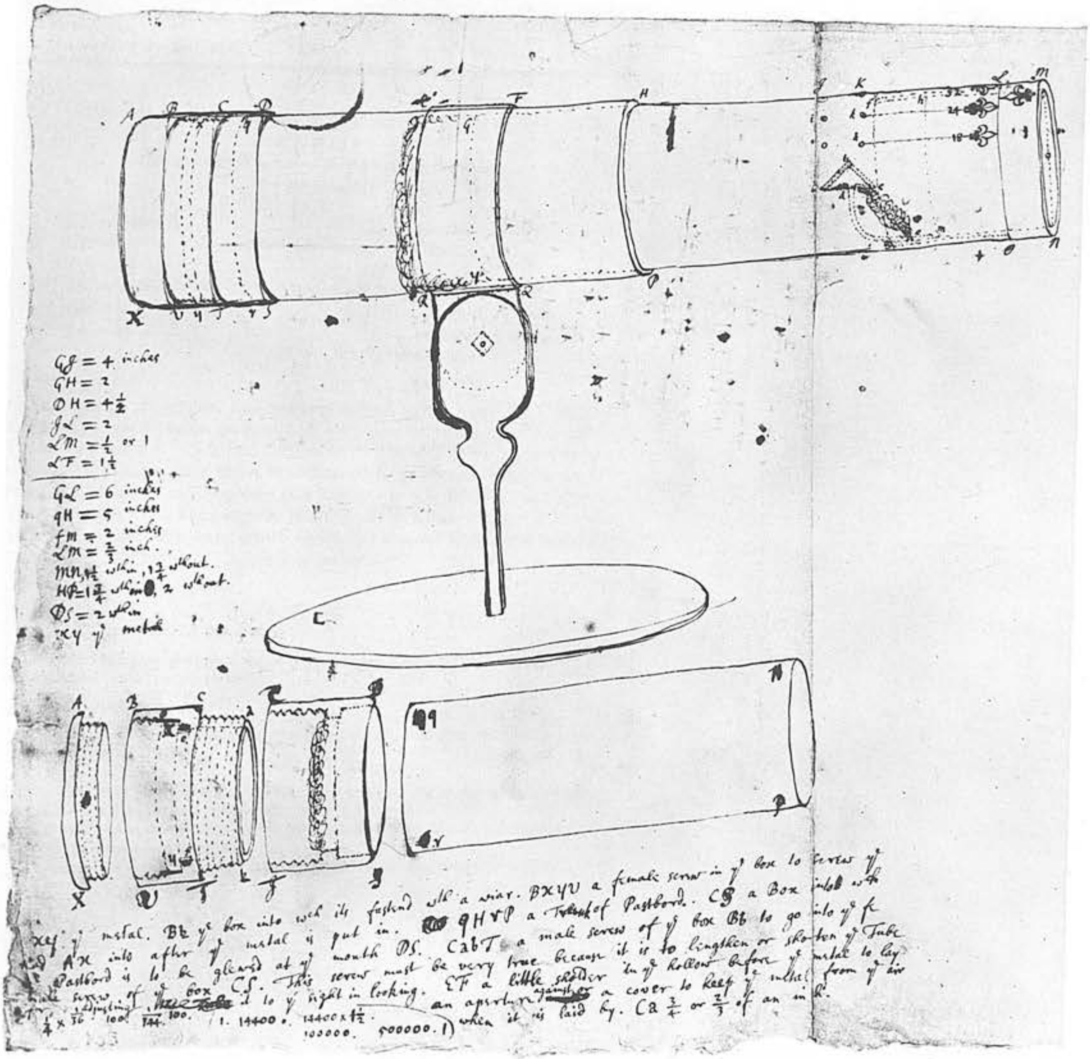

Fig.6. Design by Isaac Newton for a small reflecting telescope, 1672. Manuscript at Cambridge University Library; reproduced from Turnbull (1959).

to the mounting which is represented only in a comparatively simple form; although a number of dimensions are given, two are quoted with alternatives, suggesting they have not been taken from an actual instrument.

The most striking feature of the design is that the mirror cell, containing the mirror itself, is detachable and is screwed to the end of the barrel by a thread which is used for focusing the telescope. Newton cautioned that "This screw must be very true because it is to lengthen or shorten the tube for adjusting it to ye sight in looking." Mills and Turvey rightly point to the difficulty of retaining collimation as the primary speculum was rotated, and they prefer the simpler mechanism used (subsequently, they believe) in the 1671 telescope where the focusing screw translates but does not rotate the mirror.(5)

However, the problem is not as acute as Mills and Turvey imply. The telescope barrel is shown not as a single tube but as two concentric tubes sliding within one another, as had been used for the second telescope. Presumably then it was intended that coarse focusing at least should be by adjusting the tubes alone. The length of the threaded portion is given as "$\frac{3}{4}$ or $\frac{2}{3}$ of an inch": if the major portion of this was engaged and there was only limited rotation for fine focusing then a reasonably tight screw with little play could be achieved. The mirror is shown mounted against a circular flange or stop of aperture about $1\frac{1}{2}$", and is held from the rear by a "wiar", or spring, between the mirror and a threaded back plate. The principal collimation error would result from the axis of the focusing thread not being normal to the plane of the flange, and this could be detected in an optical test and reduced by careful adjustment to the surface of the flange. Additional adjustment could be made at the time of an observation by precise positioning of the secondary mirror, for which Newton has made allowance. More importantly, the eyepiece stop, which had been used to reduce the effective aperture to a little over an inch, appears to have been replaced by an objective stop - the flange retaining the mirror is described as "a little shoulder in ye hollow before ye metal to lay an aperture against". Although the eyepiece would benefit from a stop to reduce the effect of its own spherical figure, it would no longer have to be positioned accurately enough to mask off the outer zones of the primary speculum.

The other advantage which this type of mounting would provide is that ready access could be obtained to cover or protect the mirror surface without affecting its setting in the tube. Newton had become concerned by mid-March 1672 that the mirror of the telescope sent to the Royal Society had already become too tarnished to be useable.[6] No doubt this was very much in his mind when criticism of his new telescope was received from Auzout and Denis at the end of March. Newton found himself having to answer practical objections to the use of metallic reflecting surfaces, particularly that they would reflect less light than a lens would transmit and that the reflectivity would in any case drop rapidly as the metal tarnished. His prompt reply was largely devoted to ways of avoiding the degrading effects of tarnishing.[7] The principal cause of this was the "condensing of moisture on its polished surface wch by an acid spirit wherewth ye Atmosphere is impregnated corrodes & rusts it", and he therefore stressed the likely benefit of "diligence ... to keep it dry & close shut up from Air". Having noted that the outermost zone of the mirror is not used since it cannot be figured accurately, he added that by using this outer zone "it may also conveniently [be] fastened to ye end of the Tube on the out side, so as at pleasure to be taken off & layd up close from the Air to preserve it from tarnishing". A clear echo of this is found in the manuscript design and in the accompanying description where the flange against which the mirror is mounted may be used to support "a cover to keep ye metal from ye air when it is laid by". Although Newton did on one occasion tell Oldenburg that the speculum of the second telescope should "bee taken out and rubbed wth gentle leather" if it became dull(8), he made no suggestion of protecting the mirror at any stage before his reply to Auzout's criticisms. Since he was already aware of the speed with which the metal could tarnish(9) it would seem that there was no provision for protecting the metal other than by dismantling it from the telescope. The removable mirror cell of the manuscript scheme may at least in part reflect his concern at this time to provide simple and effective answers to the criticisms that were threatening the acceptance of the telescope. Indeed he was presumably thinking along these lines when he referred to the 'convenient' mounting on the 'out side' of the tube which allowed the mirror to be removed 'at pleasure'.

Preventing tarnishing of the flat secondary mirror, which would remain fixed in position, was more of a problem. Newton proposed that a small internally-reflecting glass prism be substituted, and this clearly remained his preferred solution as it appears in the telescope design published in the Opticks.(10) He went on to describe how stray light could be prevented from entering the prism, and how the prism could be given convex faces to act as a lens to erect the otherwise inverted image. Although this latter possibility demonstrated "one very considerable advantage of this prism wch the ovall metall is not capable of" it was nonetheless "convenient that the first trialls be made wth Prisms whose sides are all of them plane", indicating that Newton had not yet actually used a prism in this way.(11) The manuscript scheme is shown with a plane rather than a prismatic secondary, but this should not necessarily be taken to mean that the use of a prism was not intended. Firstly, the manuscript is unfinished: Newton has shown the components of the primary mirror cell in detail and has carefully described its construction; yet the complex structure at the eye end is not described, although this was presumably intended since the drawing of this end includes a number of identification letters also used at the other end. Secondly, the following folio in the volume includes, amongst some rough calculations, proposals by Newton for the testing of the optical component parts, with: "To try ye Prism se if things reflected from it appear distinct through a Perspective".(12) The test suggested here is clearly one for a plane prism rather than one with convex faces. However there is an intriguing possibility that the manuscript scheme may have been intended to show a lenticular prism. No evidence has been found elsewhere to indicate that Newton made mirrors for instruments of this general size with focal lengths longer than the 6 to 7 inches of the first telescopes. Newton appears to have moved directly to much larger instruments, but there is nothing to correspond to the 8 to 9 inch focal length required for this manuscript scheme. However if an additional erecting lens (the lenticular prism) were inserted beyond the focus of a 6 to 7 inch mirror the light would again be brought to a focus at about the position of the eyepiece. It would in fact be surprising to find such a design scheme which included all the other improvements projected by Newton and yet did not have a lenticular prism. The alternative to its use is either to admit the possibility of 8 to 9 inch focal length primaries(14), or to argue that the telescope has been shown extended and that the inner tube would not be so far withdrawn in use.(15)

The most unusual feature of the telescope depicted in the manuscript is the use of multiple eyepieces, offering a range of magnification. The eyepieces are set in fixed positions in the body tube and are brought into use by rotating a short inner tube on which the secondary mirror is mounted. The secondary is aligned with the chosen eyepiece when an index on the inner tube coincides with another on the body marked for that eyepiece. Such an arrangement is referred to once in the correspondence, in a letter from Newton to Collins for James Gregory in December 1672 after the public discussion of the telescopes had died down:

> "The charge may be also conveniently varied by having two or three eye-glasses of several depths set in a girdle, any of wch may be adjusted to the [secondary] metall F by sliding that girdle about the Tube or by sliding the ring within the Tube to wch that metall F is fastened." (16)

The three eyepieces shown in the manuscript have magnifications of 18, 24 and 32 times indicated. In itself, this is clear confirmation of a late date for the manuscript since Newton did not have to propose the use of low charged eyepieces until late March 1672 in an attempt to divert criticism of the instrument's performance by lowering the Society's expectations.(17)

The concept of multiple eyepieces seems to have arisen from James Gregory's comments of September 1672 about Newton's harsh attack on Cassegrain's proposed reflecting telescope published in the issue of the <u>Philosophical Transactions</u> which he had just received. A distinct and unrecognised advantage which Gregory saw for the Cassegrain form and his own design over that of Newton's was that by moving the secondary mirror along the axis of the tube the effective focal length of the objective (composed of the two specula) was changed, so that for a single eyepiece the magnification of the instrument could be varied. Thus, in spite of the disadvantages which Newton enumerated,

> "even with a concave or convex [secondary] speculum this telescope may be worth the trying, seing the eye glass and [secondary] speculum F being movable, the [primary] speculum CD can have, by their help, anie desirable charge; which I think a great advantage." (18)

In his December 1672 reply to Gregory, Newton demonstrated that he had conceded the value of Gregory's point, but he was able to fall back on his earlier proposal for a lenticular prism, which though initially introduced purely as a means of erecting the image, was now seen to possess this newly appreciated property of allowing the magnification to be varied.(19) One senses Newton's relief at being able to show that his own arrangement was more convenient than Gregory's in that a smaller movement of the eyeglass was required to effect the same change in magnification. It was on this occasion that the use of separate eyepieces was proposed as an alternative solution.

It might seem then that, in proposing above that a multiple eyepiece and a lenticular prism be used together, one is superfluous. However, the principal use of the prism would remain to produce the erect image which Newton by late 1672 had come to realise was desirable, and by dividing the magnification between the prism and the eyelens Newton would be able to mount all three eye lenses flush with the surface of the body tube as shown and he would require a much smaller focusing adjustment between the three settings.

The fourth distinct feature of this design is the explicit use of an alignment system to enable the instrument to be directed to an object. As with the multiple eyepieces this has not previously been commented on. The difficulty of finding objects in the second telescope had been the only initial objection made by the Royal Society[20], and since in this type of telescope the observer is looking at right angles to the direction of vision the problem is real enough. Newton was ready to admit to the difficulty, which however was an "inconvenience of all Tubes that magnify much" and he proposed that to remedy this two sights should be added to the limb supporting the body tube: he had at one time apparently thought of adding these himself.[21] The approach in the manuscript scheme however is totally different. Here a small mirror is set at an angle of 45° behind the secondary mirror, allowing the observer to take a sight through a small hole immediately alongside the eyepiece in use and past a small bead suspended at the centre of the tube's aperture. This arrangement allowed the observer to check the direction of the tube whilst scarcely having to move his head: surely a distinct advance on having to sight along the tube.

As has already been mentioned no clear evidence has been found that Newton produced telescopes of this general size after the first three: he did however proceed to larger instruments. Newton's practical interest appears to have revived in July 1672, prompted by the news that Christiaan Huygens was constructing a reflecting telescope and had exhorted Newton to continue his work:

> "touching Mr Newton's telescopes, he ought, it seems to me, to try to perfect them himself and to make them bigger in size than those of seven or eight inches." (22)

In his reply to the points raised by Huygens, Newton casually asked Oldenburg about Christopher Cock's progress with the 4 foot telescope, adding "I know not whether I shall make any further tryalls my selfe".[23] He made a point of repeating his request a few days later, asking now also about the steel speculum that had been made by Cock and whether Oldenburg could obtain a fragment of the metal for him: "I make this inquiry because if I should attempt anything further in the fabrick of the Telescope I would first inform my self of the most advantageous materialls". His serious intention was shown by his concluding question:

> " ... you will further oblige me if you can inquire whether Mr Cock or any other Artificer will undertake to prepare the Metalls, Glasse, Tube & Frame of a Four foot Telescope & at what rates he will do it so that there may remain nothing for me to do but to polish the Metalls. A gross account of this will at present suffice untill I send you a particular designe of the Fabrick of the Instrument if I resolve upon it." (24)

Cock proved amenable to the idea, and Oldenburg repeated that the mirror or "speculum-plate" which was claimed to be of "a very good metall" was fixed in a square box that attached to the end of the tube. Cock had offered

> "to unpolish this plate again, and to send you this very Instrument for 5£; and what alterations or emendations you shall direct to bee made therein, hee will make, without demanding any more mony for that labour." (25)

Oldenburg promised to send as soon as he could "a piece of that very mettal, with the said object-speculum, wch the 4 foot Telescope is compounded off"; that is, a piece of the same metal as used for the 4 foot object speculum, and not the speculum itself.[26] Cock was apparently also prepared to send the steel speculum to Newton for examination. Although this letter went astray, the piece of speculum metal was duly received by Newton (27), who was sufficiently pleased to report that it "was well for closenesse & hardnesse but yet of a colour not very brisque & inclining to red. However, if it be less apt to tarnish then any other mixture yet known, that will sufficiently recompense ye other imperfection." (28)

The missing letter with the details of Cock's telescope did not turn up, and Newton anxiously wrote:

"I feare it is miscarried & desire therefore you would favour me wth ye particulars wch were in answer to yt troublesome letter [of mine] ... for wch I begg your pardon." (29)

The letter was promptly copied for him by Oldenburg (30), but Newton had still not acknowledged it by mid-September when Oldenburg wrote to ask about his progress. On being given merely his thanks "for the trouble you was pleased to take upon you in inquiring of Mr Cock about his telescope", Oldenburg wrote "to move him to prosecute it".(31)

Whether Newton did in fact 'prosecute' the telescope is not known. No evidence has been found that the metal sample was returned to Cock(32), and it is possible that the four foot telescope may have been dispatched to Newton. At the last meeting of the Royal Society before the Summer recess it was agreed that some of the Fellows should meet at Gresham to "improve Mr Newton's reflecting telescope; and particularly to see finished a four feet Telescope of that kind, already recommended to Mr Coxe."(33) In spite of this, Oldenburg had been perfectly happy to see it sold to Newton, and it may be significant that there was no mention of the telescope in the report given after the recess or elsewhere in the minutes of the Society's meetings, although Hooke's experiments with a larger instrument were discussed on several occasions.(34) If Newton was involved in further telescope experiments, and this might account for his comment in his September letter that an earlier letter for Oldenburg had been suspended by Newton "falling upon some other business of wch I have my hands full"(35), then presumably he contacted Cock independently.

Newton does appear to have established and maintained personal contact with Christopher Cock, and in late 1679 he added a postscript to a letter to Hooke, that

> "Mr Cock has cast two pieces of Metall for me in order to a further attempt about ye reflecting Tube wch I was ye last year inclined to by ye instigation of some of our Fellows. If I do any thing you may expect to hear from me. But I doubt ye tool on wch they were to be ground, being in ye keeping of one lately deceased, who was to have wrought ye metals, is lost." (36)

In this we have the only definite evidence that Newton was involved in any practical work on speculum telescopes after mid-1672, and it is not even clear whether it was pursued. The extract however does emphasise Newton's reliance on the assistance of specialist craftsmen such as Cock, seen also in his earlier correspondence with Oldenburg about the four foot telescope. This raises the possibility that in the manuscript scheme for the small telescope Newton may have been preparing the specification for a telescope tube to be made by such a craftsman, rather as he had earlier proposed to send Oldenburg "a particular designe of the Fabrick of the Instrument" he was then contemplating.[37] The manuscript scheme certainly concentrates on the mechanical elements and omits detail of the optical components: the construction is described and dimensioned, and the dimensions for which there are alternatives given are ones where discretion could reasonably be left with the maker. The commercially available microscopes and smaller telescopes of this period had bodies of paste-board tubes, often sliding within one another, and covered in coloured vellum with a gold-tooled decorative finish: the lenses were contained in turned cells of hardwood. G.L'E.Turner has demonstrated that the tubes of surviving instruments made before 1700 have distinct features in common, and he has proposed that these were the specialised work of the turner Jack Dunning, acting as sub-contractor to all the major opticians and supplying instrument bodies in which they would insert their own lenses.(38) Hooke is known to have bought tubes from Dunning, and there is a dated telescope signed by Cock among the instruments considered by Turner.(39) The quality of workmanship required for the telescope shown by Newton is certainly comparable with that seen in instrument bodies attributable to Dunning. The only unusual feature was the long focusing screw thread which had to be "very true"; however, threads of this diameter were being cut successfully, so that this ought to have been readily obtainable by a turner of Dunning's undoubted skill.(40)

Cock would have contracted out of the casting of the metals mentioned by Newton in 1679, as he did earlier for Hooke, and apparently the grinding of the metals was also being done by another optical worker. The implication is that Cock was merely co-ordinating the job for Newton, and therefore perhaps that he had remained Newton's principal contact with the optical workshops. E.G.R. Taylor has identified the "one lately deceased, who was to have wrought ye metals" as Richard Reeves, on the basis of his earlier association with Cock in reflecting telescope work, and she has therefore used Newton's comment to establish Reeves' date of death.(41) Another possibility however is that he was a turner named Smethwick, also patronised by Hooke, whom Taylor described as "apparently partner of Jack Dunning" working also "as a glass-grinder, making lenses for the telescopes and other optical instruments for which tubes were supplied".(42) A possible association of Smethwick with work on reflecting telescopes is provided by Hooke in a cryptic comment in his diary for 1678 that he had "Returned Dunning Reflex metall".(43)

Notes and References

1. Turnbull (1959), plate II. The manuscript, U.L.C. Add 3969 f591, is transcribed by Turnbull as item 31: ibid, 77.
2. Ibid, 104 n17.
3. Mills & Turvey (1979), 135 and plate 12.
4. Whiteside (1969), 439 n23.
5. Mills & Turvey (1979), 135.
6. Turnbull (1959), 121: letter of Newton to Oldenburg, 19 March 1671/2. The condition of the instrument was described in a lost letter from Oldenburg of 16 March.
7. Ibid, 126: letter of Newton to Oldenburg, 30 March 1672. Reply to a lost letter from Oldenburg received after 26 March in which he passed on comments by Adrien Auzout and Jean Denis.
8. Ibid, 80: letter of Newton to Oldenburg, 6 January 1671/2.
9. Ibid, 121: letter of Newton to Oldenburg, 16 March 1671/2, referring to the performance of the second telescope being affected by "a little tarnishing of the Metall in 4 or 5 days of moist weather".
10. Newton (1704) I, 79.
11. Turnbull (1959), 128: letter of Newton to Oldenburg, 30 March 1672.
12. Ibid, 77 n4: transcription from U.L.C. Add 3969 f592.
13. Using the quoted dimensions (which however incompletely specify the optical arrangement) the foci would not be symetric about the prism, but this would in any case be a necessary consequence of the use of relatively low power eyepieces.
14. The existing telescope at the Royal Society has a mirror of focal length of about 8.2" and Mills & Turvey (1979), 147, have found it to have the same composition as the speculum alloy proposed

by Newton in the Philosophical Transactions. The apparently long focal length required for the instrument in the manuscript scheme (together with the assumed date of the manuscript) has led them to conclude that Newton's earliest mirrors were of this type. The dating proposed here would require long focal length mirrors, if they were produced, to have been made after mid-1672.

15. The inner tube is shown to extend into the outer by a stated dimension of 2", which apparently denies this possibility. Similarly the length would have to be reduced by over 2" and so the outer tube would overlap the eyepiece in use, unless the dimensions given are not accurate.

16. Turnbull (1959), 250: letter of Newton to Collins, 10 December 1672.

17. Ibid, 124: letter of Newton to Oldenburg, 26 March 1672.

18. Ibid, 240: letter of Gregory to Collins, 23 September 1672.

19. See above, ref (16).

20. Ibid, 73: letter of Oldenburg to Newton, 2 January 1671/2: "it was longsome & difficult to find ye Object: wch inconvenience yet they looked upon, as possible to be remedied"

21. Ibid, 80: letter of Newton to Oldenburg, 6 January 1671/2.

22. Hall & Hall (1973), 118: translation of letter Huygens to Oldenburg, 21 June 1672 (O.S.). This extract was included in the section transcribed and sent to Newton in Oldenburg's letter of 2 July 1672: Turnbull (1959), 206.

23. Turnbull (1959), 212: letter of Newton to Oldenburg, 8 July 1672.

24. Ibid, 217: letter of Newton to Oldenburg, 13 July 1672.

25. Ibid, 219: copy of a letter of Oldenburg to Newton, 16 July 1672.

26. Idem.

27. Newton was corresponding with Oldenburg from Northamptonshire, but returned to Cambridge on 19 July 1672: Edleston (1850), lxxxv. On 30 July he wrote that he had acknowledged the metal's arrival "last week", i.e. 20-26 July.

28. Turnbull (1959), 221: letter of Newton to Oldenburg, 30 July 1672, repeating the comments he had made in his letter of 20-26 July.

29. Idem.

30. Ibid, 221 n2. Turnbull's suggestion (ibid, 238 n3), that the copy was not sent until 17 September is based on an over-literal interpretation of Oldenburg's notes on Newton's 13 July letter (ibid, 218 n1) where "my last of July 16" must mean "my last letter copying the July 16 letter". Newton's profuse apologies on 21 September for not replying sooner would be unnecessary if he had received the copy only two or three days beforehand.

31. Ibid, 237: letter of Newton to Oldenburg, 21 September 1672; and ibid, 238 n1.

32. Hall & Hall (1973), 160, say that the specimen was returned, but I can find no reference to this in the correspondence.

33. Roy. Soc. MS Journal Book, meeting of 10 July 1672.

34. Ibid, meeting of 30 October 1672.

35. Turnbull (1959), 237. If Newton did indeed still have his 'hands full' then this can hardly have been the production of his edition of Varenius' Geographia Universalis which appears to have been completed by the end of July.

36. Turnbull (1960), 303: letter of Newton to Hooke, 9 December 1679. After Oldenburg's death in 1677 Hooke became a Secretary of the Society and in late 1679 opened the present correspondence with Newton on motion under gravity. Turnbull proposed that Newton

was influenced by the Society's experiments on metal alloys, but these experiments were begun only in December 1679. It is possible that the "instigation of some of our Fellows" may have been some considerable time beforehand, possibly even when Newton was first admitted to the Royal Society in February 1675 and is known to have discussed speculum polishing methods with Hooke: Robinson & Adams (1935), entry for 18 February 1674/5.

37. Turnbull (1959), 217: letter of Newton to Oldenburg, 13 July 1672.

38. Turner (1966), 124.

39. Robinson & Adams (1935), entry for 15 November 1676. The telescope is signed "Christopher Cock Londini/1673": Turner (1966), 107.

40. The signed telescope by Cock (now Science Museum, London, Inv. 1926-419) was described in more detail by Baxandall & Court (1926), who illustrated (fig. 3, p.532) a section through the turned components of the telescope tube. The eyelens is held in a wooden mount and is attached to the outermost body tube. The mount screws into a ring which carries a complex internal stop and which is glued to the end of the tube; and the eyelens is then covered by an eye cup, which is also attached by a screw thread. The diameter of both threads is $2\frac{1}{4}$". This three-part structure has close similarities to the type of cell proposed in Newton's manuscript scheme, and it indicates comparable thicknesses for the surfaces on which the threads were cut. The required clearances have been obtained by fitting the cell to the outside of the outer tube, as is shown in Newton's scheme.

41. Taylor (1954), 224. The date has not been verified from another source. The reference by Clay & Court (1932), 253, to Reeves' activities in 1689 is more reliably attributed to John Reeves by Court & von Rohr (1929-30), 75.
42. Taylor (1954), 269. This Smethwick was not the same as Francis Smethwick, maker of conic section lenses.
43. Robinson & Adams (1935), entry for 4 April 1678. This is presumed to have been a concave speculum, but it may perhaps have been a flat speculum for a helioscope-type instrument.

3.10b The 'Telescopii Novi Delineatio'

In the course of James Gregory's extended correspondence with Newton in 1672 and 1673 Gregory proposed a design for a burning mirror made of glass with a reflecting rear surface.(1) The radii of the front and rear surfaces of the glass were computed for a specified refractive index so as to bring the light reflected from the two surfaces to the same focus. The design, which had been conceived some years beforehand when Gregory was working on a revised edition of the Optica Promota, was well received by Newton, who suggested a simplified form with the two surfaces ground to the same radius of curvature.(2) His later experiments with telescope mirrors of this form are discussed in the following section.

It may be however that Gregory's burning mirror suggested to Newton the possibility of mirrors in which the glass of the mirror acts as a lens.(3) Certainly about this time he devoted concentrated effort to the problems of such a compound lens/mirror instrument, and a number of variant drafts exist among his optical manuscripts of a "telescopii novi delineatio", or outline of a new telescope. The 'Delineatio' was first published in recent years by Turnbull, and has since been published in extenso by Whiteside and commented on by Bechler.(4)

Newton's intention has been to construct a reflecting telescope in which the effective size of the primary is increased by using in addition a thin convex object-glass. In this he may also have been stimulated by his correspondence with Gregory, in which the restricted aperture necessary to reduce the effect of spherical aberration had been an important point of discussion. The mirror is in the form of a concave meniscus lens with a reflective rear surface, and no doubt this type of mirror would have been attractive to Newton as it represented one method of avoiding the tendency of metal mirrors to tarnish, an aspect of the performance of his reflector that he had been concerned about since early 1672.(5) He had already proposed that the small secondary mirror be replaced by a prism in which the light would undergo total internal reflection, and such a prism is shown in the 'Delineatio'. The ability to protect the second reflecting surface would however have been a notable improvement.

It was some years apparently before he carried out practical trials of a glass mirror. The mirror he used was one in which the two radii of curvature were the same, and Newton was somewhat surprised to find that reflection from the front surface of the glass was not as troublesome as he had expected. The 'Delineatio' may have been Newton's earliest consideration of glass mirrors, and it is perhaps significant that the form he has adopted avoids this particular problem. Perhaps influenced by Gregory's ability to make the foci coincide, Newton has developed an optical scheme in which light reflected from the two surfaces comes to separate foci.

The importance of the design is that Newton has used a convex and a concave lens in conjunction with the reflecting surface in such a way as to form an achromatic system. Having used glass to protect the mirror surface and an object-glass to increase the aperture, the instrument was obviously doubly prone to the damaging effects of chromatic aberration. Whilst Newton was successful in devising conditions to minimise this aberration, Bechler has commented that

> "It is perhaps ironic that, in order to safeguard this projected improvement of his original reflector, Newton had first to resolve the problem which he had been reluctant to tackle for the pure refractor." (7)

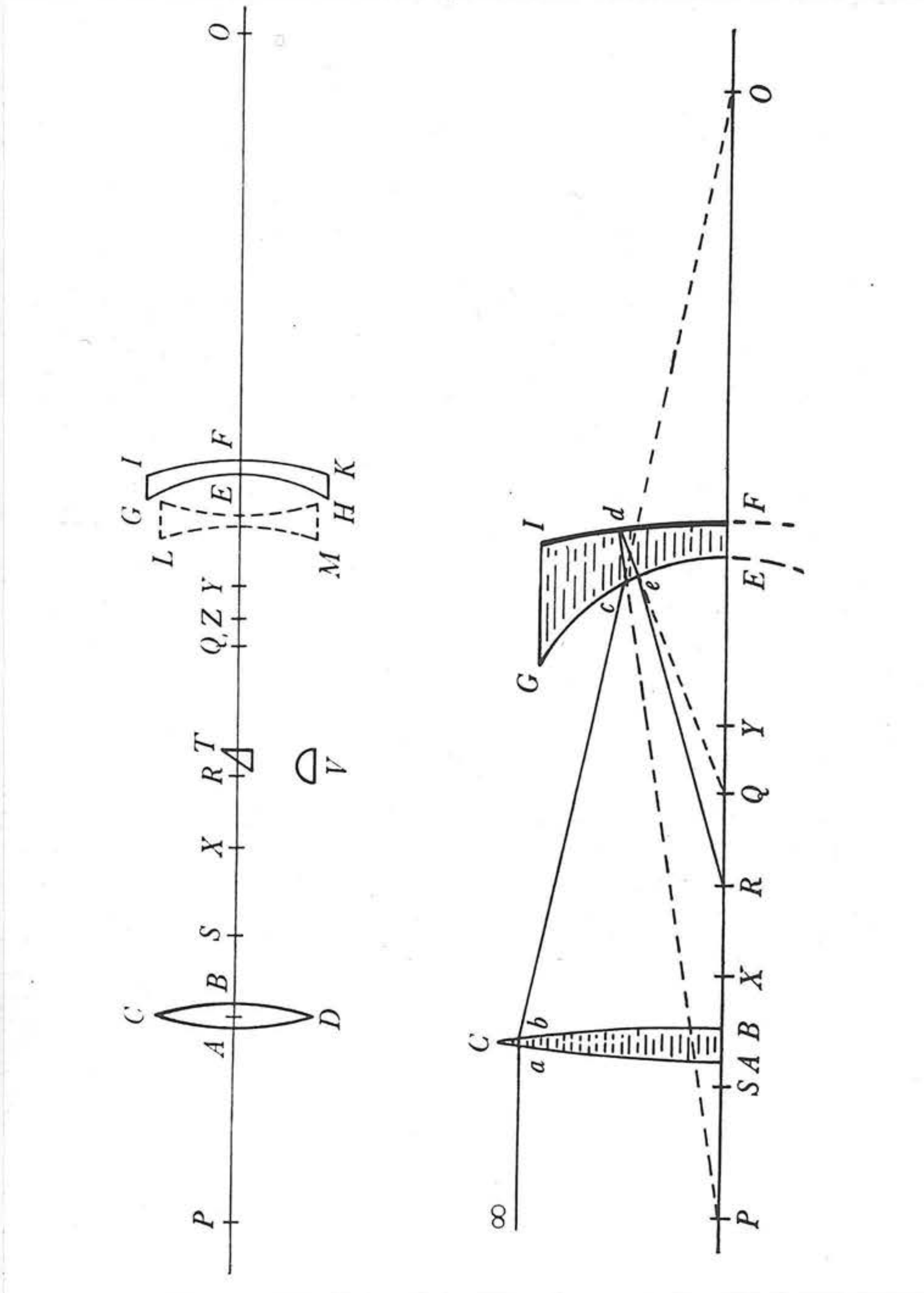

Fig.7. Optical components for a compound reflecting telescope by Newton, 1673(?), with an explanatory ray diagram. Reproduced from Whiteside (1969).

Incident light parallel to the axis of the telescope is refracted by the object glass CD to O, the position of which is of course dependent on the colour of the ray. For a given colour therefore the ray is refracted towards a particular point O, but then refracted again at the front surface of the mirror of radius EY to a virtual image P. Reflection at the rear surface of radius FX is towards Q, but a further refraction at the front surface deflects the ray through R. The point R then forms the focus for this colour of light, and the light is then deflected at right angles to the axis by a prism T towards the telescope eyepiece V.[8] However, for the telescope to be effective, Newton had to demonstrate that, by a suitable choice of the lens separation and of the radii of curvature of the surfaces, the point R could be made the focus for light of all colours. To establish the criteria for this, Newton considered the mirror as comprising a notionally separate reflecting surface and a concave lens[9], and he defined a point S which was the ideal image of the three refractive elements of the system and acted as the ideal source for the reflecting element. But if R is the image of S in the rear surface only, ignoring the presence of the lens, and if R is to be the focus for light of all colours it follows that S is the ideal achromatic image point of the refractive elements. Thus, in Newton's words,

> "the angular translation of the image from O to P and from P to S [is to] be as much as is sufficient to correct errant refractions arising in the object glass from unequal refrangibility" (10)

On the assumption that the lenses are thin and that the angles of deflection are small throughout, Newton derived the relationship BE : EO = EO : ES that defined the position of S. The steps required to obtain this condition were not given by Newton but have been reconstructed by Turnbull and Whiteside.(11) It is not my intention to repeat this, but merely to note that it was obtained by applying Newton's general theorem for refraction and reflection at single spherical surfaces to the refraction, reflection and subsequent refraction at the surfaces of the mirror, together with the similar relationship linking S and R. From these was derived an equation linking the positions of O and S in relation to E with the constants for the lens system and the refractive index. The condition for minimising the chromatic effect is that for slight changes in the refractive index (and therefore of the position of O) the position of S (and therefore of the final image point R) is invariant, and therefore that the derivative of the equation is set to zero, and this yields Newton's requirement.

Bechler's principal reason for analysing the lens-mirror telescope has been to demonstrate

> "that Newton was in full command of a mathematical solution to the general problem of achromatism in lenses, even though he actually applied this method to a compound whose elements included a mirror and only one sort of refracting medium. There was ... no difficulty in principle, in applying this method to a system of more than one refractive medium and no mirrors so as to obtain an achromatic compound lens along the lines described by him in his reply to Hooke." (12)

Bechler has concluded from a study of the variant drafts of the reply to Hooke that Newton privately believed in the feasibility of achromatic lenses, but that he attempted to suppress discussion of them, since he saw such an admission as damaging to his own theory of light. Bechler has provided a logical extension of Newton's treatment of the lens-mirror telescope to demonstrate how the method might have been applied to compound lenses, as indeed it was in the eighteenth century when Newton's suppression of achromaticity was first appreciated. Of this method, Bechler finds it

> "hard to accept that a man of Newton's genius would find the alterations indicated above in the lens-mirror problem so difficult as to render the main notion of the 'Delineatio' inoperative in the compound lens variant ... However, Newton, though deeply interested in his 'new telescope' ... never contrived to publish it, and the notion, which could have been seminal in the seventeenth century, remained unknown until its recent publication." (13)

Notes and References

1. Turnbull (1959), 260: letter of Gregory to Collins, 7 March 1672/3.
2. Ibid, 271: letter of Newton to Collins, 9 April 1673.
3. Ibid, 276 n1.
4. Ibid, 272; Whiteside (1969), 526; Bechler (1975), 116. Bechler also proposes that the description was prompted by his correspondence with Gregory, but he sets the date at 1672.
5. See the section 'Reaction to Newton's Telescope'.
6. See the following section.
7. Bechler (1975), 117.
8. Although Newton's diagram shows a prism, the description mentions a "slanting mirror".
9. This may also account for the double concave lens LM indicated on the diagram.
10. Whiteside (1969), 527. Bechler unfortunately concludes from this that, if the reflecting surface was removed from the rear of the mirror and the ray allowed to emerge, then S would be its virtual image point, whereas it is clear from Newton's requirements (and Bechler's definition of S) that its position must take account of the second refraction at the front surface of the mirror. This does not effect the validity of his argument, but his second condition for S must be re-cast (p.118).
11. Turnbull (1959), 274; Whiteside (1969), 527 n38. Bechler couches the equations in a different form, but the intermediate steps are confused by typographic errors: Bechler (1975), 118 n34.
12. Bechler (1975), 116.
13. Ibid, 119.

3.10c Glass Objective Mirrors

At the end of the first part of Book I of the Opticks, Newton described the optical construction of an ideal reflecting telescope, incorporating presumably those features which with hindsight he considered the most promising and practical.(1) The primary mirror was to be contained at the end of a tube blackened within; the secondary was to be a small internally reflecting prism, with convex faces if the image was to be erected; the aperture of the plane-convex eye-lens was to be restricted by a stop; guidelines were laid down for the relationship of focal length, aperture and magnification, and these were specified for a 6 foot tube. The only way in which the instrument differed from previous published designs was that the primary mirror was of glass:

> "Let ABCD represent a Glass spherically concave on the foreside AB, and as much convex on the backside CD, so that it be everywhere of an equal thickness. Let it not be thicker on one side than on the other, lest it make Objects appear coloured and indistinct, and let it be very truly wrought and quick-silvered over on the backside ... Such an Instrument well made if it be 6 Foot long [defined as the focal length], will bear an aperture of 6 Inches at the Speculum, and magnify between two and three hundred times ... But its convenient that the Speculum be an Inch or two broader than the aperture at the least, and that the Glass of the Speculum be thick, that it bend not in the working." (2)

The reasons given for proposing a change from metal to glass mirrors were predictably the difficulty in polishing metal, its low reflectivity and its tendency to tarnish. A glass mirror of this type had in fact been made for Newton, but had not proved entirely satisfactory:

> "By such a Glass I tried about five or six Years ago to make a reflecting Telescope of four Feet in length to magnify about 150 times, and I satisfied my self that there wants nothing but a good Artist to bring the design to Perfection. For the Glass being wrought by one of our London Artists after such a manner as they grind Glasses for Telescopes, tho it seemed as well wrought as the Object Glasses use to be, yet when it was quick-silvered, the reflexion discovered

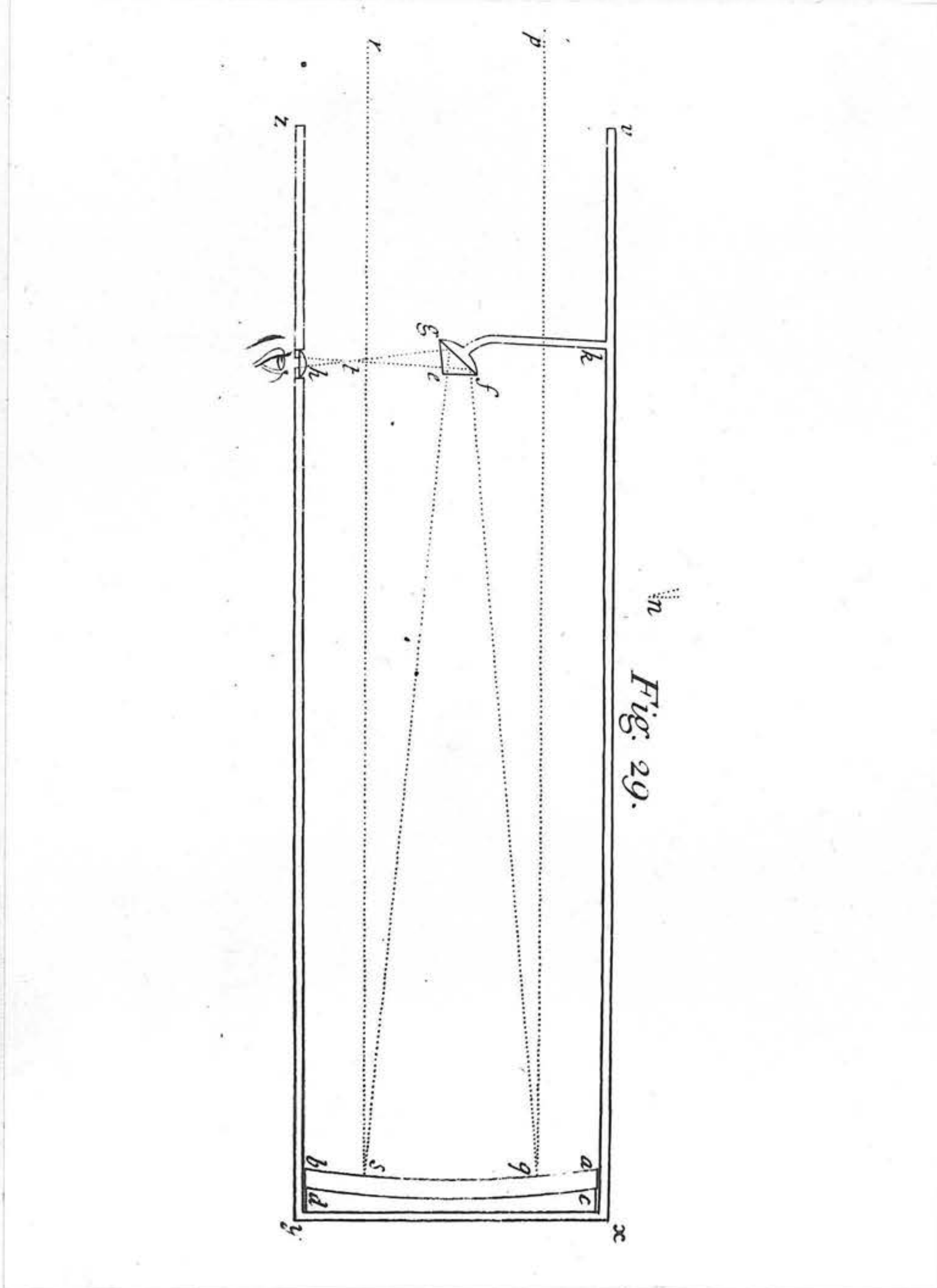

Fig.8. Diagram by Isaac Newton of a glass-mirror reflecting telescope from his Opticks of 1704.

innumberable Inequalities all over the Glass. And by reason of these Inequalities, Objects appeared indistinct in this Instrument. For the Errors of reflected Rays caused by any Inequality of the Glass, are about six times greater than the Errors of refracted Rays caused by the like Inequalities. Yet by this Experiment I satisfied my self that the Reflexion on the concave side of the Glass, which I feared would disturb the vision, did no sensible prejudice to it, and by consequence that nothing is wanting to perfect these Telescopes, but good Workmen who can grind and polish Glasses truly spherical." (3)

It has already been shown in connection with the third telescope that dates in Book I have been adjusted to be consistent with the supposed date of writing, so that the production of this glass "about five or six years ago" implies a date of about 1682.(4) This comes not long after Newton's attempt to work large speculum metal mirrors, and so the use of glass mirrors may be seen as a sequel to the earlier attempt, and perhaps a consequence of its failure. The concept of such mirrors was certainly not new, since Gregory had suggested their use as burning glasses in 1673.(5)

Although this particular speculum of Newton's may not have been of sufficient quality for a telescope, he may have pressed it into use in other experiments; if it was the mirror used in a diffraction experiment at the end of Book II of the Opticks then its focal length was 3 foot rather than 4 foot:

" ... I let the intromitted beam of Light fall perpendicularly upon a Glass Speculum ground concave on one side and convex on the other, to a Sphere of five Feet and eleven Inches Radius, and Quick-silvered over on the convex side ..." (6)

Newton's concern that the optical workers could not "grind and polish Glasses truly spherical" he justified by describing how:

"An Object-Glass of a fourteen Foot Telescope, made by one of our London Artificers, I once mended considerably, by grinding it on Pitch with Putty, and leaning very easily on it in the grinding, lest the Putty should scratch it. Whether this way may not do well enough for polishing these reflecting Glasses, I have not yet tried." (7)

The "violence wherewith our London Workmen press their Glasses in grinding" also bent the glass and this led to a distorted figure. This lens described by Newton above may be the same one referred to in an observation of diffraction rings sent to the Royal Society in December 1675:

> " ... I took two object-glasses, the one a plane-convex for a fourteen foot telescope, and the other ..." (8)

The only other reference found to an optical instrument maker in the Opticks occurs when Newton described how when he had made the second telescope "an Artist in London undertook to imitate it". Newton had subsequently discoursed with "the under-Workman" he had employed: this may mean a craftsman working under Cock or, more likely, Cock working for Hooke.(9) From the known association with Cock in 1672 and 1679 it is tempting to suggest that Cock remained Newton's link with the London workshops and that he was the maker of the glass mirror.

Notes and References

1. Newton (1704) I, 79: Proposition VIII 'To Shorten Telescopes'.
2. Ibid, I, 79-80.
3. Ibid, I, 77-78. Newton's statement about surface inequalities may be derived as follows. For near normal incidence a small change of x^{o} in the angle of incidence will produce a change of about $2/3\ x^{o}$ in the angle of the refracted ray in glass; thus a small inclination of the surface of x^{o} will deviate the refracted ray by $x - 2/3\ x = 1/3\ x^{o}$, compared with the equivalent deviation of a reflected ray of $2\ x^{o}$.
4. Brewster (1855) I, 52, proposed a date of 1678. I presume this was suggested by Newton's 1679 correspondence with Hooke, which has already been discussed, in which Newton referred to an attempt at constructing a reflecting telescope the year before.
5. Turnbull (1959), 260; letter of Gregory to Collins, 7 March 1672/3.
6. Newton (1704) II, 88. The experiment may not be dateable since this section of the Opticks was described as having been "put together out of scattered Papers".
7. Ibid, I, 78.
8. Birch (1756-7) III, 274, repeated in Newton (1704) II, 5. A further, but less likely, possibility is that the lens was a double-convex objective of focus 168½" used in a late (but undateable) repeat of one of the 1675 experiments, inserted in the Opticks but not present in the original paper: ibid, II, 9.
9. Ibid, I, 76.

CHAPTER 4 THE 18TH CENTURY REVIVAL OF THE REFLECTING TELESCOPE

4.1 THE WORK OF JOHN HADLEY

Newton's telescope had almost faded from view by the beginning of the 18th century, but it was not forgotten. In 1704 John Harris (1666-1719, F.R.S. 1696), a lecturer in practical mathematics in London, produced his famous work the Lexicon technicum, in which he drew on the writing of the greatest authorities of the day to form what was in effect the first general scientific encyclopaedia. In mathematics, physics and astronomy Harris turned to Newton, and he included a half page account of the 'Reflecting Telescope of Mr Newton' drawn from the Philosophical Transactions of 1672.(1) The work had a strong practical and instrumental emphasis, with Harris giving some prominence to the best London instrument-makers of the time, such as John Marshall and John Rowley, and it proved very popular.

With the publication of Newton's Opticks in mid 1704, however, the reflecting telescope was again thrust to the fore. Not only had its role in the historical development of the optical theory been enhanced, but Newton now provided considerable technical detail about its construction and included the design for an enlarged and improved form, both clearly intended to stimulate experimentation and to stem any criticism of the instrument's practicability.(2) Although Flamsteed claimed that "The book Makes no Noyse in Town as the principia did", it is clear it was well received.(3) The reputation of the Principia had created a ready market, and the more readable Opticks with its appeal to simple experiment, and with a style that Cohen has described as an intimate, gentle English, enjoyed a success that was by no means restricted to scientific circles.(4)

John Harris' Lexicon ran through three impressions, and in 1710 he brought out a second volume intended to complement the first. The entry for the reflecting telescope reappeared, this time with an account extending over three pages derived from the Opticks and including the illustration of the proposed glass-mirror telescope.[5] By late 1710 the instrument certainly provided a topic for discussion[6], and more important, professional instrument-makers were beginning to experiment with it.[7] Von Uffenbach recorded a visit to the workshop of the London mechanician John Rowley in October 1710 when:

> "Rohly showed us various objective glasses ... which he recommended highly. ... He had two more convex-concave glasses, which he intended to mount and use for a reflecting telescopio of Newton. He praised the invention of Newton very highly, as though it were quite matchless. These last two glasses were tolerably polished and better than the objective ... He valued them at seven or eight guineas each." (8)

However, if we may judge from comments made in the early 1720s when larger reflectors were at last successfully made, such early trials were not noticeably effective.[9]

The credit for constructing the first reflecting telescope of a practical size falls to John Hadley (1682-1744, F.R.S. 1717) whose name is more usually associated with the invention of the reflecting quadrant in 1730. Hadley's few writings were restricted to his scientific activities and we know little of his life. The small amount of biographical information available resulted from historical researches of S.P. Rigaud, Savilian professor of astronomy at Oxford and Royal Astronomer at Kew, in the 1830s, and his account has remained the standard (if little known) source.[10]

John Hadley was the eldest son of George Hadley, deputy lieutenant and later high sheriff of Hertfordshire. Nothing is known of John's education, but at the time of his election to the Royal Society in 1717 he was a proficient mathematician and had a highly competent mechanical ability.(11) His father's town house in Bloomsbury was close to that of the eminent physician and natural historian Sir Hans Sloane, Vice President of the Royal Society, and it is clear that Sloane was on familiar terms with John and his younger brothers George and Henry. It is assumed that it was Sloane who introduced John Hadley to the Royal Society, and that it was under his patronage that Hadley was first elected to the Council in 1720.(12) He became Vice President shortly after Sloane had been raised to the presidency on Newton's death in 1727, and he held this position until his death.(13)

The second English edition of Newton's Opticks was published later in the year of Hadley's election to the Society, and it may have been this that first prompted Hadley to consider how the telescope might be realized in practice. Lalande subsequently stated that he had undertaken his work "a l'instigation de Newton", but although Newton would no doubt have wished to encourage such a project, his role (if any) in the affair is unknown.(14) Hadley was assisted in his experiments by his brother George, who had been called to the bar in 1709, and Henry, who returned in 1719 from his medical studies in Leyden.(15) Both were subsequently to play a part in the development of John Hadley's reflecting quadrant: George undertook its actual construction and wrote the pamphlet describing its use, whereas Henry conducted some of the first sea trials.(16)

Hadley's telescope construction attempts met with success, and he made a Newtonian reflector with a metal mirror about 6" in diameter and about 5'3" focal length. Samuel Molyneux, writing some years later, said that the work was performed "about the year 1719 or 20".(17) Certainly an instrument was operating in the Spring of 1720, when

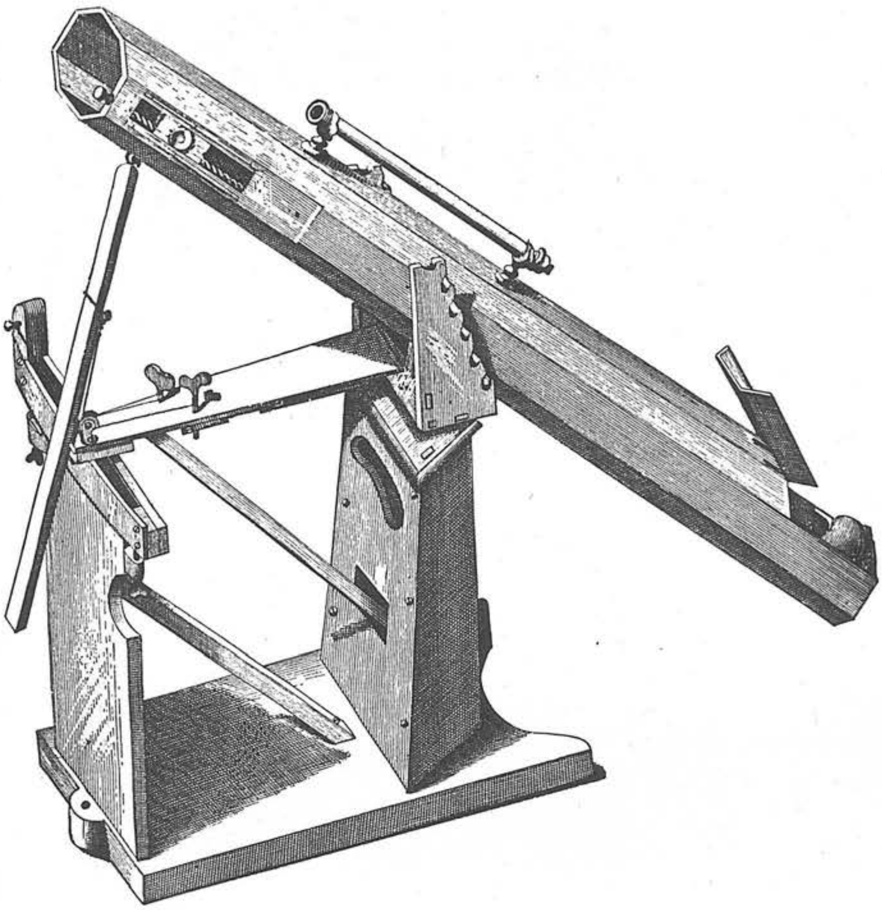

Fig.9. Five foot reflecting telescope by John Hadley, 1720, as reproduced from the Philosophical Transactions for 1723.

Hadley made an observation of Saturn.(18) In fact, two identical mirrors were produced, but Hadley made no mention of having followed Newton's procedure of polishing mirrors in pairs and trying to improve one against the other.(19) Hadley retained one telescope and the other was presented to the Royal Society in January 1721:

> "Mr Hadley was pleased to shew the Society his reflecting Telescope made according to our Presidents [Newton's] directions in his Opticks, but curiously executed by his own hand, the force of which was such, as to enlarge the object near 200 times, tho the length therof scarce exceeds Six foot, and having shewn it he made a present thereof to the Society who ordered their hearty thanks to be recorded for so valuable a gift". (20)

The telescope was to be sent to Edmond Halley for his use at the Royal Observatory at Greenwich and Hadley was asked to give Halley a demonstration. At the Society's meeting a week later Hadley produced the telescope again, but now mounted on an original and effective stand of his own devising, which met with approval "both for its Simplicity and for the ease and certainty with which it performs the motions requisit to follow the heavens". Evidently this was the stand for his own instrument, for he was urged to lend it to Halley so that he could "have one like it made at the Society's Charge to be used with his noble present".(21)

Although there is no doubt that the instrument was warmly received, no account of it was published until 1723, by which time it was clear that the instrument indeed answered the Society's expectations. The account which eventually appeared in the <u>Philosophical Transactions</u> was a careful description of the instrument itself, but did not give any details of Hadley's method of producing the mirrors.(22) The octagonal wooden tube had a hinged portion at its lower end, allowing the mirror, once a handle had been screwed into its rear surface, to be extracted from the mirror cell. When in place, the mirror was held gently against three small flanges within the tube by screws which passed through the end of the tube. The aperture was altered by laying card rings over the mirror to obscure the outer zones. The oval secondary mirror was mounted to a wooden block which could be moved along a slot in the side of the tube by a focusing screw, and which also contained the mount for the eyepiece. A selection of convex and concave eye pieces were provided, together with a compound lens with an erector "which turns it into a Day Telescope". A small refractor mounted on the tube acted as a finder. The novelty of the stand was that Hadley had contrived it so that the observer could control the instrument by turning two conveniently placed pegs.

Halley was impressed with the telescope, and he reported that he had tried it on Jupiter and Saturn and he believed it might be found to excell "even the great telescope at Wanstead".(23) This instrument was the aerial telescope which had been lent to the astronomer James Pound (1669-1724, admitted F.R.S. 1713), Rector of Wanstead in Essex, in 1717. Its objective was the Society's 123 foot focus lens by Constantine Huygens, and it was supported on the old maypole which Newton had arranged to have removed from the Strand.(24) Pound's great skill as an observer had enabled him to repeat planetary observations previously only made with the best Continental instruments, and he was anxious to make a comparison with Hadley's new instrument. The telescope was sent to him, and his observations with it are first recorded in June 1722.(25) For a number of years Pound had been assisted in his astronomical work by his nephew James Bradley (1693-1762, F.R.S. 1718), subsequently Astronomer Royal. Earlier in the year Bradley had taken up his appointment as Savilian professor of astronomy at Oxford, but he was still able to make regular visits to

Wanstead and now began a series of comparative observations of eclipses of Jupiter's satellites using the reflector and various refractors.

In his report to the Society, Pound expressed himself satisfied that provided a method of preventing the metals from tarnishing could be found"the old Dioptrick Telescope will be for the most Part laid by" and the reflector take its place.(26) For all their great difference in size, the definition of the two instruments was found to be about the same, although the Huygens refractor gave the brighter image. Pound and Bradley were particularly impressed with the ease with which Hadley's instrument could be directed, and with their confirmation of the earlier observations of Halley, and of Hadley himself, they had clearly demonstrated the practical potential of the instrument.

Pound died in 1724, but Bradley continued to stay regularly with his aunt, and it was in her house that he set up his famous zenith sector in 1727, with which he made the observations that led to his description of stellar aberration and nutation.(27) Although the Huygens telescope was returned to the Royal Society in 1728, Bradley continued to use the reflector at Wanstead periodically until his increased teaching commitment at Oxford caused him to move there permanently in 1732, after which there is no mention of the instrument.(28)

He was appointed to Greenwich in 1742, and in 1749 he moved the zenith sector, but the fate of the reflector is unknown. The mirror and a number of eyepieces turned up in the Royal Society's collection and were identified as from the Hadley telescope by Rigaud in 1834.(29) These are now on loan to the Science Museum, London.(30)

Two early and apparently independent accounts, both of which may be dated to 1725, stated that Hadley made two Newtonians, and no mention has been found of other instruments of this type made by him.[31] One of the two apparently remained with Hadley, and Rigaud has proposed that it was this instrument which was to be demonstrated to J.N. Delisle in late 1724.[32] Rather than try to develop the Newtonian further, Hadley was working at the Gregorian form and apparently produced the first of this type in 1726. A description of this was published in 1735 by J.T. Desaguliers; and a diagram of the instrument is said to show one with a perforated metal primary of 2" diameter and 12" focal length, and the eyepiece has a field lens "to prevent the object being coloured at the Edges of the Aperture".[33] The size is not necessarily particular to an instrument since Hadley had added tables giving the optimum dimensions for instruments of 3" to 27" focal length for day or night use.[34]

A small Gregorian telescope, with a speculum of 2" diameter and 8" focal length, was preserved in the Hadley family and was described by Hadley's nephew in his will as "the first of the sort that ever was made, invented by my late uncle, John Hadley, Esq. and made under the direction and with the assistance of his two brothers, George and Henry."[35] Rigaud interprets this as meaning the first Gregorian telescope to be made, but then assumes that it was made by John Hadley assisted by his brothers. However, considering the prominent role that George played in the construction of the first reflecting quadrant in 1730, the reference should perhaps be interpreted as meaning that the instrument was made by George and Henry, working under John's direction, as several other followers had done. The instrument is now in the Science Museum, London, and carries an engraved plaque, composed in 1874 and based on Rigaud's article, which attributes it unambiguously to John alone.[36]

Details of Hadley's methods of grinding and polishing mirrors were given by Robert Smith in his Compleat System of Opticks in 1738.(37) The early part of the account was written by Samuel Molyneux who had been instructed by Hadley, and obviously despaired of Hadley ever committing the method to paper:

> "had he ever given himself the trouble to reduce to writing what he knows and hath practiced in ... the manner of casting, grinding and polishing of the specula ... the following account had been altogether unnecessary." (38)

To Molyneux's discussion of the casting and rough grinding of the speculum, written before his death in 1728, Smith added a description said to be by Hadley of the construction of the tools, and the figuring and polishing of the speculum. An account of the complete process, clearly similar to the one published, was sent by Smith to James Bradley, who had collaborated with both Molyneux and Hadley, at the end of 1732.(39) Hadley was to be asked to give his comments on this, so it is possible that Hadley's contribution to the published version may have been to revise an earlier and more complete account by Molyneux.

The method described was complex and involved a number of separate processes. A beam compass, with the required radius of curvature of the mirror, was used to mark two flat brass plates, which were then cut to form a convex and a concave template. When these had been ground against one another they were used as the gauges to which the various tools and the mirror itself were referred. The mirror was cast in an iron mould lined with sand and clay, using a pattern already turned on a lathe to the correct concavity. The composition of Hadley's early alloys is not known: Molyneux later used tin, copper and brass in different proportions and recommended a composition of equal parts of copper and brass with slightly over half as much tin.

Once cast, the concave surface of the metal was ground "quite bright upon a common grindstone" to remove irregularities. A grinding stone which had already been ground to the correct convex shape with sand, was then used to grind the metal to the gauge limit using progressively finer emery with water. By varying the type of grinding stroke Hadley could control the mirror's curvature, which was increased by using circular strokes and reduced by diagonal strokes.

A brass tool somewhat larger than the mirror was then cast in brass and turned concave on a lathe. A convex slab of marble had squares of the finest whetstone or 'hone' cemented to it, and this was used to fine-grind the tool. The tool was then used to form the polisher, which was a glass disc accurately ground convex in the tool using emery and finally covered with pitch-impregnated silk. The tool and the mirror were then alternately ground on the hones to obtain a more accurate figure until they were "all over equally bright". The polishing of the mirror could now begin, using a little putty as an abrasive; but if the curvature of the mirror was found to have altered slightly from that of the polisher, the tool had to be used to correct the curvature of the hones, and the mirror re-figured until its shape exactly matched that of the polisher.

With luck this exhaustive procedure produced a fairly good spherical surface which could then be tested optically. To do this Hadley used approximations to point sources placed at the centre of curvature of the mirror and examined the shape of the images. Regrinding of the hones was necessary if the images were distorted, but if not the final polishing could be done. Before this however, Hadley attempted to impart a parabolic figure to the mirror, although strictly this was not necessary for mirrors with such a small aperture ratio. Particular strokes of the mirror on the hones at the very end of the grinding process were used, and the change in figure could be observed by examining the image of a point source with an eyepiece, as before, and noting how the image flared as the eyepiece was moved longitudinally.[40]

Notes and References

1. Harris (1704-10): Vol. 1, art. 'Telescope, Reflecting'.
2. Newton (1704) I, 75-80.
3. Scott (1967), 424: letter of Flamsteed to Pound, 15 November 1704.
4. Cohen (1952), xxii, xxxvi.
5. Harris (1704-10): Vol. 2, art. 'Telescopes'.
6. John Caswell, Savilian professor at Oxford indicated his disapproval of the instrument to von Uffenbach on 6 October 1710: Mayor (1911), 392.
7. William Derham had travelled to London in June 1704 to see Newton's "new Contrivance of Reflecting glasses", but this was a burning mirror and not a reflecting telescope. Atkinson (1952), 381.
8. Quarrell & Mare (1934), 168 (28 October 1710).
9. E.g. Pound (1723), 382. R.T. Gunther ascribed an early Gregorian reflector in the Orrery Collection (No. 12) to c1710, but based this on a mistaken belief that an illustration of this type of mounting appeared in the 1710 edition of Harris: Gunther (1923), 314, 315. William Derham may have been influenced by such trials as were undertaken: in late 1711 he was testing a new 100 foot objective by Marshall and told Sloane that "I have a pretty strong conceit I can improve Sir Isaac's Catoptrical Telescope: but the expense it would put me to, makes me find the want of a small additional preferment ...". Sloane worked to secure this but it was Samuel Molyneux who had Derham appointed chaplain to the Prince of Wales in 1716: Atkinson (1952), 384, 386.

10. Rigaud (1832a) and Rigaud (1833-4) on the invention and history of Hadley's quadrant; Rigaud (1835) on the Hadleys, including a brief account of their telescope work. S.P. Rigaud was identified as the author of these in the Nautical Magazine 4(1835)12; his name was not recorded however in the reprinted versions subsequently produced as pamphlets with new pagination. These pamphlets were the sources of the entries for the Dictionary of National Biography (1890) and the Dictionary of Scientific Biography (1972), whose authors merely cited them as anonymous. They were also used by Brewster, who was however aware of the author's identity: Brewster (1855) I, 54 n1.
11. Rigaud (1835), 17 repeats J.T. Desaguliers' claim that Hadley had patented the water power device used at London Bridge. He was however only ten years old when the patent was granted in 1693, and so it seems most likely that the patentee was a different John Hadley.
12. The association must have been well established between Sloane and the Hadleys by 1715: in this year Henry left to begin his medical studies in Leyden, from which he graduated in 1718 dedicating his thesis to Sloane: ibid, 650.
13. Ibid, 137 and note.
14. Ibid, 21. This may merely refer to the statement that the telescope had been made "according to our President's directions in his opticks": see below, ref (20).
15. Ibid, 530, 651. Rigaud apparently based these statements on the known collaboration of the brothers ten years later, and on the description in the will of John Hadley's nephew, Hadley Cox, of a reflecting telescope of c.1726 made "with the assistance of his

two brothers, George and Henry": ibid, 536. It is therefore also possible that George and Henry became involved with this work only after the first two instruments had been made.

16. Rigaud (1832a), 350; Rigaud (1833-4), 343; Rigaud (1835), 530, 651.
17. Smith (1738), 302.
18. Hadley (1723a), 385.
19. Newton (1704) I, 77.
20. Roy. Soc. MS Journal Book, meeting of 12 January 1720/1.
21. Ibid, meeting of 19 January 1720/1.
22. Hadley (1723).
23. Rigaud (1835), 19. It is not clear whether this report was made in March 1720/1 or March 1721/2, although it appears to have been the latter: the original has not been found.
24. Atkinson (1952), 388.
25. Rigaud (1832), 354.
26. Pound (1723), 382-4.
27. Rigaud (1832), lxxv, 197; Howse (1975), 60-4.
28. Roy. Soc. MS Journal Book, meeting of 28 June 1728; Rigaud (1832), 364. His observations of eclipse times of Jupiter's satellites were used by him in 1728 to deduce longitude differences between Lisbon, New York and London, and he commented on the consistent discrepancy between the times of observations made with reflectors and refractors - an effect later to be investigated by Maskelyne: Bradley (1728); Forbes (1975), 139-40. In 1750 when writing to Delisle he made it clear that his Jupiter observations had been made with a reflector "made by the late Mr John Hadley, and presented by him to the Royal Society": Rigaud (1832), 462.

29. Rigaud (1835), 657: for the negative result of his early enquiries see _ibid_, 19. The mirror (which incidentally was attributed to Hadley by the compiler of the 1827 inventory) was described by Simms as "ancient & imperfect" and is numbered 81 in the 1834 published list. Bradley's patron, the Earl of Macclesfield, set up an observatory at Shirburn Castle, close to Oxford, in the late 1730s, and Bradley was a frequent observer there. Macclesfield, who was President of the Royal Society from 1752 to his death in 1764, borrowed the Huygens apparatus and this was returned in a number of crates by his widow. It is quite possible that he had been lent the Hadley reflector by Bradley and that the mirror was returned at the same time.

30. Inv. No. 1932.459. Besides the mirror and its handle, there are five of the six original eyepieces, but only one (a concave) has its lens. The convex eyepieces are marked with magnifications that correspond with the description in Hadley (1723), 306: I, 190; II, 210; III, 230.

31. These accounts by Molyneux and Hauksbee are discussed in the following section. Rigaud believed in 1832 that Bradley had used another 5' Newtonian by Hadley at Greenwich and that this was the instrument then in the hands of a descendant, Richard Best of Greenwich: Rigaud (1832), xi. Subsequently he described this instrument as a 6' used from 1753 and does not claim its construction by Hadley: Rigaud (1835), 537. It is presumed that this was the 6' Newtonian supplied by James Short in 1756, which was in use until 1785 and had a rather similar construction to the Hadley instruments: Howse (1975), 113, 115, fig 105. Rigaud did not believe Short had delivered this instrument: Rigaud (1832), lxxix.

32. Letter of Hadley to Sloane, 8 September 1724, reproduced only in the off-printed version of Rigaud (1835).

33. 'An Account of the Gregorian Reflecting Telescope, as perfected, by John Hadley, Esq; Vice-President of the Royal Society, in the Year 1726.' in Desaguliers (1735), 250-6.

34. Ibid, 253-4. These were revised in December 1734, ibid, 285-8, and Hadley mentioned in his letter to Desaguliers that he had given a similar table of sizes for Cassegrain telescopes to Samuel Molyneux.

35. Rigaud (1835), 536. John Cox died in 1782.

36. Inv. No. 1939.601. Correspondence about the inscription, and the owner's copy of Rigaud's off-print, are included in the specimen's Technical File. See Thoday (1971), item 6.

37. 'The method of casting, grinding and polishing metals for reflecting telescopes, begun by the Honourable Samuel Molyneux Esquire, and continued by John Hadley Esquire, Vice-President of the Royal Society' in Smith (1738), 301-312.

38. Ibid, 302.

39. Rigaud (1832), 401-3.

40. Smith (1738), 311.

4.2 THE START OF COMMERCIAL MANUFACTURE

However diffident John Hadley may have been about publishing his technique of working telescope mirrors, he was certainly active in helping others to experiment. One of those to benefit from what he described as Hadley's "communicative genius" was the Hon. Samuel Molyneux (1689-1728, F.R.S. 1712), son of William Molyneux the Irish astronomer and natural philosopher.(1) Through his father, who had a personal acquaintance with Huygens and had published a notable work on optics, his Dioptrica Nova, in 1692, Samuel Molyneux developed an early inclination for astronomy. His wife brought him a sizeable fortune, and the inheritance of Kew House in 1721, and this he established as an observatory, and directed his efforts to astronomy and practical optics. He was a close friend of James Bradley, and through his influence as Secretary to the Prince of Wales, Molyneux had been able to advance Bradley in the Church.(2) The two men worked together at Kew, and it was there that they installed the zenith sector with which Bradley discovered the effect of stellar aberration. Before this, however, they were active in constructing reflecting telescopes, again at Kew, and working under Hadley's guidance.

It was to Molyneux and Bradley that Robert Smith (1689-1768, F.R.S. 1718), Plumian professor of astronomy at Cambridge, turned for the account of Hadley's methods that he used in his influential Compleat System of Opticks of 1738. Molyneux had died ten years beforehand, and his account was probably written in mid 1725. Having described Hadley's Newtonians, he added:

> "Upon his encouragement and instructions, the Reverend Mr James Bradley Professor of Astronomy in Oxford, attempted the same about three years ago; and having succeeded pretty well, would probably have perfected one of them, had he not

> been obliged suddenly to remove from the place where he dwelt, and been since diverted from it by other avocations. Soon after this Mr. Bradley and I began our endeavours at Kew to perform the same, and our first attempt was to make them about 26 inches long. Notwithstanding Mr. Bradley's former tryals and Mr. Hadley's frequent instructions, we were a long while before we could tolerably succeed." (3)

Their first real success was with an instrument of 26" focal length, finished in May 1724. This may well have been the telescope described and illustrated later in Smith's Opticks as having been presented by Molyneux to John V of Portugal, presumably for his observatory at Lisbon.(4) The hexagonal wooden tube for this was depicted as being very similar to Hadley's earlier instrument, but was mounted on a simple geared pillar, set however on a suitably opulent triangular table; it was said to perform as well as a refractor of 35-40 foot. When Molyneux's account was written, he and Bradley were still working on an 8ft instrument, but although Bradley later recorded an observation of Jupiter made with this instrument, nothing further is heard of it.(5)

Another who evidently received Hadley's guidance was J.T. Desaguliers (1683-1744, F.R.S. 1714), curator of experiments to the Royal Society and a successful exponent of the newly popularised demonstration lectures in natural philosophy. The historical account of reflecting telescopes he appended to the 1735 edition of David Gregory's Elements of Catoptrics and Dioptrics contributed to an awareness of the new instrument, and in this he mentioned details "sent me, by Mr. Hadley, for my private Assistance in making that Instrument", probably in 1726.(6)

More significant however was the practical help given to Francis Hauksbee the younger (1688-1763), since he achieved some success and his was the first commercial venture. Hauksbee was nephew to the more famous instrument maker of the same name who had been curator of experiments to the Royal Society before Desaguliers. As his uncle had done, Hauksbee made a wide range of instruments in his shop, which was adjacent to the Society's house, and also offered courses of experimental philosophy. By 1723 when he was appointed clerk and housekeeper to the Society he was already well known to "divers Members of the Society" who had recommended him for the post. In a pamphlet issued probably in early 1725 Hauksbee described how he had been sufficiently encouraged by Hadley's success with the reflecting telescope "to attempt the same thing, especially having the Advantage of his Kind Advice and Assistance; and I have accordingly made two Telescopes of three Feet and $\frac{1}{4}$ long each".(7) Robert Smith later concluded from reports he had of tests conducted on one of these by Hauksbee, James Jurin and Martin Folkes that it "was wrought ... to so great a perfection as to magnify 226 times; and therefore to be scarce inferior to Mr. Hadley's" even though it had a shorter focal length.(8)

Hauksbee's instruments were made as a speculative venture for public sale, reckoned at the time to be a risky undertaking. The purpose of Hauksbee's pamphlet was to invite subscriptions to give him the financial encouragement to tackle mirrors of 6ft and 12ft focus. Subscribers, at a guinea a time, were to be given special opportunities to view the heavens with the instrument and a number of gentlemen had already promised to support this proposal, "whose Success cannot but contribute to the Improvement of Knowledge and Philosophical Learning." Hauksbee "deserves very well to be encouraged" in this proposal, wrote Molyneux, "being the first person who hath attempted it without the assistance of a fortune, which could well bear the disappointment."(9)

The purpose of the trials made by Molyneux and Bradley was "to reduce the method of making these instruments to some degree of certainty and ease" so that instrument makers would no longer be discouraged by the risk of failure.

> "About the beginning of the last winter being pretty well satisfied as to most of the circumstances in this performance, and being desirous that these instruments might become cheap and of publick sale, we acquainted Mr. Scarlet near St. Anne's Church, and Mr. Hearne a Mathematical Instrument-maker in Dogwel Court, White Friers, with the whole process of the operation as we had practised the same; and they have since succeeded in making these instruments. However as they are not yet become so common, so cheap or so universally made and used, as one would wish an instrument of this nature to be, we have been encouraged to give this following account ..." (10)

The mid 1725 dating of the 'historical preface' to Molyneux's account of the mirror grinding process is satisfactory elsewhere, but suits this concluding passage less well. Possibly this was added by Molyneux before he handed over his papers to Smith in late 1727, so that the instruction of Scarlett and Hearne would have been in 1726 and not 1724.(11) This would be more in line with Desaguliers' claim that Hadley, having developed his first Gregorian telescope in 1726, had

> "since taught his Majesty's Optician Mr. EDWARD SCARLETT, and his Son, to make both the Sorts; which they do so well, that I have not yet known them exceeded in these Instruments by the Performance of any other Optic-Glass-Grinder". (12)

The Gregorian form would certainly have had greater appeal for an instrument-maker such as Scarlett, who catered for the interests of an enquiring clientele which had little serious astronomical inclination and would probably be interested in the instrument as much for the ingenuity it displayed and as a diversion for terrestrial

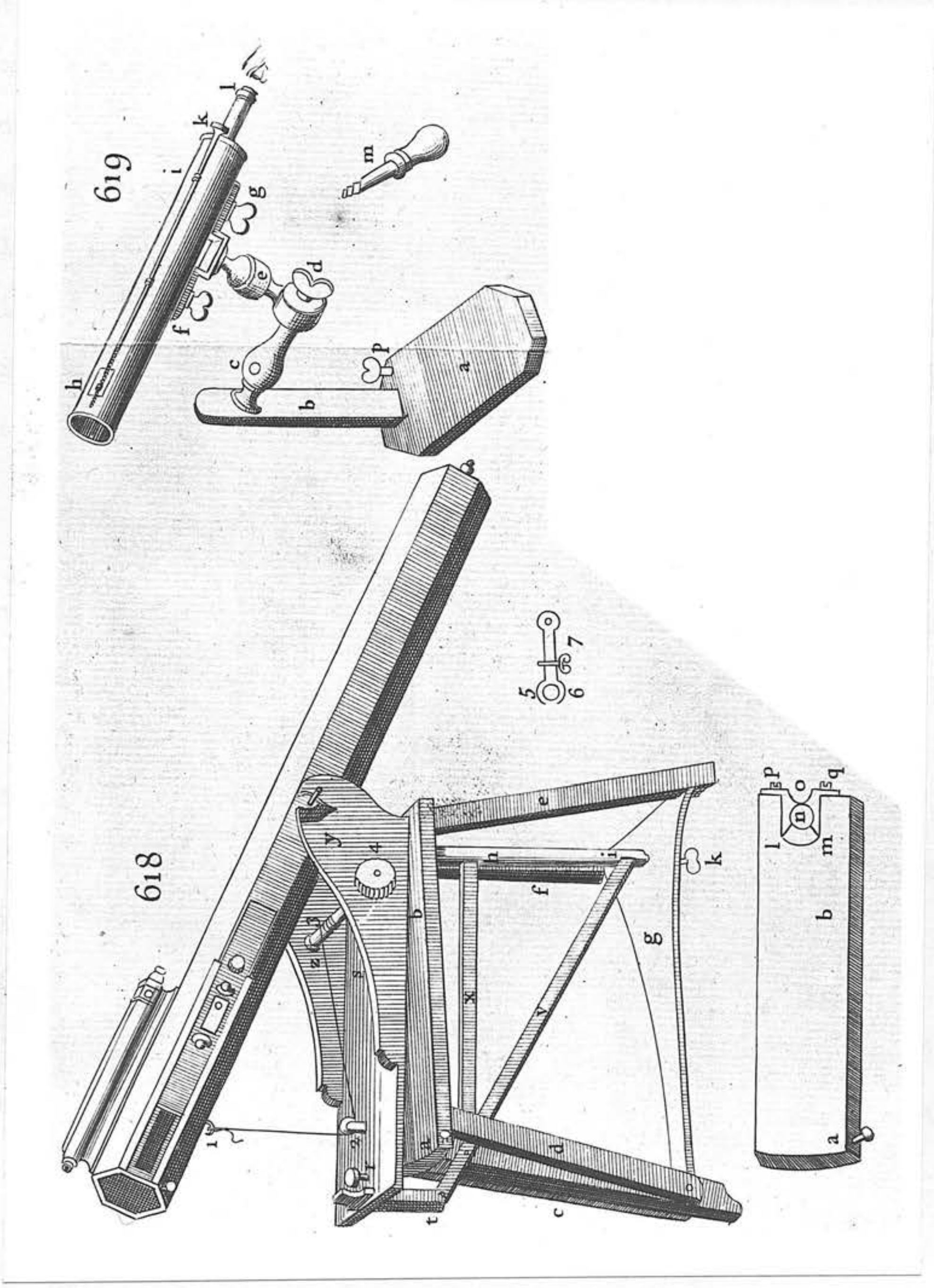

Fig.10. Newtonian telescope attributed to George Hearne, and small Gregorian telescope attributed to Edward Scarlett, c.1730, from Robert Smith's <u>Compleat System of Opticks</u> (1738).

use. Smith illustrated an instrument of the type produced by Scarlett, "and generally made about 16 inches long". This had a double knuckle joint attaching the brass tube to an arm which could be screwed either into a wooden stand or into any handy tree or upright wooden post in which a hole had been bored using the hand auger provided. Examples of this construction are in the Court Collection at the Science Museum, London, and the Orrery Collection at the Museum of the History of Science, Oxford.(13) A telescope by Scarlett which is mounted on the lid of the instrument's box is in the Royal Scottish Museum.(14) Edward Scarlett junior completed his apprenticeship with his father in 1724, and it may have been he who was responsible for making the mirrors, for which the firm was soon well known. It was that "excellent workman, Mr Scarlett jun" who made the prototype of Robert Barker's reflecting microscope, described in 1736, which was merely a small reflecting telescope used in reverse.(15)

George Hearne, the optical and mathematical instrument-maker, was responsible for a number of large reflecting telescopes produced about this time. He was a member of neither the Spectaclemakers' nor the Grocers' Companies, and the extent of his working life is not known. He was associated with Molyneux by at least late 1726, and in 1727 he made the support of George Graham's zenith sector for Bradley which he remounted at Greenwich in 1749.(16) There is no definite information however about any earlier activities by Hearne. It is of course tempting to suggest that Hearne had obtained the initial metal mirror blanks for Hadley, and then on Hadley's recommendation had supplied blanks to Molyneux and Bradley also. Molyneux paid great attention to the metals and claimed to have experimented with 150 different alloys and several casting methods, and perhaps Molyneux turned to Hearne to supervise or undertake this work also.(17) The illustration reprinted by Smith of a large Newtonian is clearly one of Hearne's instruments and matches in detailed construction the 5ft instrument used by Smith himself. The stand was described as being "to Mr Hadley's design a little altered by experience", and constructional similarities may indicate a common source for the furniture of the instruments.(18) Continuity of this type might explain why the otherwise obscure George Hearne was one of the two instrument-makers subsequently instructed in speculum making.

Smith described his telescope in a footnote to Molyneux's instructions for casting specula as being "made by that excellent workman Mr. Hearne in Dogwel Court".(19) Although the design of the stand is apparently discussed in a chapter contributed by Molyneux, it is included in the final sections which were added later by Smith, and so its date is uncertain. The instrument was presented by Smith to his Cambridge college, and was kept in Trinity College Library until its recent move to the Whipple Museum of the History of Science, Cambridge.(20) A more elaborate stand was provided for the larger telescope made by Hearne in 1734 for W.J. s'Gravesande, professor of astronomy and mathematics at Leiden. The instrument had a focal length of 7ft and its construction was supervised by Bradley.(21) In addition to having the normal motions, the horizontal plane could be inclined to allow the instrument to operate as an equatorial near the meridian. Hearne also supplied a 5ft telescope for use by J.N. Delisle at the Imperial Observatory founded by Peter the Great at St. Petersburg. Delisle's observations of Jupiter's satellites made with this instrument from May 1735 were sent to Bradley in 1738 for comparison with his own.[22]

E.G.R. Taylor has described the instrument-maker Joseph Jackson as having a business association with Hearne.[23] Possibly this would have been from about 1730 when Jackson's apprenticeship to Thomas Heath would have ended: Jackson's independent activities seem to begin in 1735 when he obtained his freedom in the Grocers' Company and booked his first apprentice.[24] It may have been an earlier association with Hadley that led to Jackson obtaining the rights to manufacture Hadley's reflecting octant for the ten year period of protection provided by his November 1734 patent.[25] Certainly Jackson was already skilled at grinding telescope mirrors in 1736: this is the likely date of pamphlets, based on Robert Barker's account of his reflecting microscope, which described this pattern of combined reflecting telescope and microscope as being "Made and Sold only by Joseph Jackson".[26] John Mudge, who was closely interested in the casting and grinding of speculum alloys in the third quarter of the century, had a high opinion of Jackson's specula. Jackson had been able to increase the proportion of tin to make the metal very white, but also "so exceedingly hard, that it cost him an infinite deal of pains, and a journey of two hundred miles, to find out a stone of sufficient hardness to cut it, and whose texture at the same time was fine enough not to injure its surface."[27] If there was indeed an association between Jackson and Hearne, then it is possible that Jackson may have been responsible for the mirrors of Hearne's large instruments, or at least may have been instructed by Hearne.

Whereas Hearne seems to have been alone in constructing larger instruments, for which there was a very restricted market, the smaller

Gregorian instruments proved a popular enough sale item for Scarlett, and soon a number of other opticians began to produce them also. In 1736 the Royal Society arranged for a series of comparisons to be made between reflectors by different makers.(28) Four of Scarlett's telescopes were examined and performed satisfactorily when directed at the standard test object - a page from the Philosophical Transactions. His largest instrument was a Cassegrain telescope with a 4" aperture mirror of 2 foot focal length, and therefore with an additional lens in the eyepiece to give it an acceptable erect image. Initially it performed well, but it was then noticed that "some accident displaced one of the Metals: so that it became indistinct": perhaps to guard against his instruments being mishandled again Scarlett was present at the next test. Two 9" Gregorians by a Mr John Chaplain of London, who is otherwise unknown, were found to be of good quality, but another of the same size by James Mann II (c1685-1750) was disappointing, "representing Objects very faint and indistinct: so we set it by."

Although the signatures of a number of makers appear on telescopes at this time, it is clear that specialist makers to the trade were soon active. Joseph Jackson appears to have acted in this capacity, as perhaps did John Cuff (c1708-72), who had been apprenticed to Mann and was free in 1730. Both Mann and Cuff advertised that they sold optical instruments wholesale as well as retail; and Cuff may have been the maker of a group of three Gregorians of c1740 at the National Maritime Museum for which a common source has been suggested.(29)

Notes and References

1. Smith (1738), 302.

2. Clerke (1886), 167.

3. Smith (1738), 302. The interruption to Bradley's work was probably the start of his duties as Savilian professor at Oxford, where his inaugural lecture was given in April 1722: Clerke (1886), 167.

4. 'Sir Isaac Newton's reflecting telescope made and described by the Honourable Samuel Molyneux Esquire, and presented by him to his Majesty John V, King of Portugal: ...': Smith (1738), 363 and Plate 53. The description is apparently taken from instructions sent with the telescope: thus, the speculum when not in use is to be kept "in the round cell in the red box." For John V see Daumas (1954), 127.

5. On 18 August 1725: "the 1st Sat. of Jupiter immerged by an 8f. reflect. at Kew": Rigaud (1832), 356. This, together with a reference to Hauksbee's activity dates this part of Molyneux's account to about mid 1725.

6. Desaguliers (1735), 255.

7. Hauksbee (1725), 1.

8. Smith (1738), Remarks, 79. The telescope aperture is stated to be $4\frac{1}{2}$".

9. Ibid, 302.

10. Ibid, 303.

11. Ibid, 281. Molyneux's appointment was in July 1727.

12. Desaguliers (1735), 212.

13. Baxandall (1922-3), 315: Inv. no. 1918.106.

14. Bryden (1968), 29: Inv. no. 1968.75.

15. Bradbury (1968), 3-4.

16. Rigaud (1832), lxxv.

17. Smith (1738), 304.

18. Ibid, 366-7, Plate 54, fig. 618; reproduced here as Fig. 10, p.307.

19. Ibid, 304.

20. Gunther (1937), 204, plate opp. p.205. Edleston describes it as being shown to visitors as Newton's own telescope: Edleston (1850), xlvi.

21. De Sitter (1933), 16. The telescope is now in the Rijksmuseum voor de Geschiedenis der Natuurwetenschappen, Leiden, and is described in Engberts (1970), 13-4, Fig. 3: Inv. no. A10.

22. Rigaud (1832), 412-5: letter of Bevis to Bradley, 5 August 1738.

23. Taylor (1966), 181.

24. Brown (1979), 36-7.

25. Patent 550 of 22 November 1734. Rigaud (1833-4), 209, citing William Wales.

26. Brown (1979), 75.

27. Mudge (1777), 298.

28. An account of the comparison was prepared by John Bevis and read at the Royal Society on 16 December 1736: Roy. Soc. MS LBC.23.88-95.

29. National Maritime Museum (1970), 31-3, 31-4. We can deduce that Cuff did make specula himself since he signed a mirror of c1745 at the Whipple Museum of the History of Science, Cambridge (No. 422): ibid, 31-4.

4.3 JAMES SHORT'S EARLY TELESCOPES

The London tests of 1736 were undertaken because the opportunity had arisen to examine telescopes by a new and talented maker from Edinburgh, who was then briefly in London. This was James Short (1710-68, F.R.S. 1737), a student and protegé of the mathematician Colin Maclaurin, who with Maclaurin's encouragement had begun to make reflecting telescopes with considerable success, both technical and financial. He was soon to move to London where he rapidly became established as the premier telescope maker, supplying instruments to the majority of the observatories of Europe.

A number of detailed studies of James Short's life and his contribution to scientific instrument making have been published by D.J. Bryden and G.L'E. Turner.(1) More recently Mr Turner has discussed the explosive interest in scientific enquiry, and hence in scientific apparatus, during the 18th century, and the markets and patronage that supported makers such as Short.(2) I have drawn on these for the brief outline of Short's early work below.

James Short was the son of an Edinburgh artisan, but was orphaned at the age of 10. He showed great promise at school and was able to attend Edinburgh University. He is reputed to have completed the arts course in 1731, which would normally have led to a career in the Church, but like many of his contemporaries he did not graduate. His late 18th-century biographer David Erskine, Earl of Buchan, recorded how

> "having had occasion to attend a course of Mr Maclaurin's mathematical class, in the College, he soon lost all relish for his ecclesiastical prospects; and made so great a figure in the class, that the professor took great notice of him, and invited him often to his house, where he had an opportunity of knowing more fully the extent of his capacity." (3)

Colin Maclaurin (1698-1746, F.R.S. 1719) was a zealous disciple of Isaac Newton, and the great man had petitioned on Maclaurin's behalf to help secure for him the chair of mathematics at Edinburgh in 1725. The size and popularity of Maclaurin's Edinburgh lectures enabled him to divide his students into several classes and teach a comprehensive course of Newtonian mathematics and natural philosophy. Thus, having received a grounding in the mathematical discipline including surveying and astronomy, the third class "went on in astronomy and perspective [optics], read a part of Sir Isaac Newton's Principia, and had a course of experiments for illustrating them, performed and explained to them" before tackling fluxional calculus and the remainder of the Principia.(4) Maclaurin also gave popular evening lectures in Experimental Philosophy in the winters of 1730 and 1731, and in the latter course he laid special emphasis on optical experiments.(5)

Maclaurin had spent some time in London in 1719, when he had been elected to the Royal Society, and in 1721, and had met many of the Fellows and formed lasting friendships with several, notably Martin Folkes and George Graham.(6) Through these personal contacts, and his subsequent correspondence, Maclaurin was aware of Hadley's work and of the renewed interest in the reflecting telescope. Inevitably, Maclaurin's university and extra-mural lectures will have included a discussion of the nature of chromatic aberration, and its elimination in Newton's telescope. No doubt he also described the work of John Hadley and others that had led to the successful manufacture of reflectors. He may also have had the opportunity to demonstrate such an instrument since the new London-made Gregorians may by now have been available to him, and indeed attempts were already being made to construct reflecting telescopes locally. D.J. Bryden has described how Hugh and William Barclay, sons of an Edinburgh minister turned spectacle-maker, made two reflecting telescopes in 1730 and 1731, adopting the rather unusual method of selling them by raffle in the hope of obtaining suitably high prices.(7)

Bryden has suggested that it was probably a combination of the stimulus of Maclaurin's lectures and the example of the activities of the Barclays that led Short to experiment in practical optics. According to Buchan, Short had already demonstrated considerable practical aptitude, and "In the year 1732, Mr Maclaurin kindly permitted Mr Short to use his rooms in the College for his apparatus; and there he began to work in his profession under the eye of his eminent master and patron".(8)

Initially Short worked with glass, perhaps because glass was more readily available, but more probably because glass mirrors had been recommended by Newton as the most promising. He eventually mastered the difficult task of grinding and polishing the matched surfaces required for back-silvered mirrors, but was frustrated by defects in the glass which were only apparent when the mirror had been polished.(9) However, six were successfully produced, three each of 9" and 15" focal length, and Maclaurin was able to get some of these placed with suitably influential purchasers. The quality of these instruments was clearly good since with his 15" telescope Alexander Bayne, professor of Scots law, was able to read the Transactions easily at 280 feet.

In spite of the apparent success of his glass mirrors, speculum metal proved an attractive alternative: Short found that he was able to get a higher reflectivity, but, more important, only one surface had to be formed and he was no longer dependent on the internal optical quality of the material. By December 1734, when Maclaurin wrote a glowing account of Short's work to Robert Smith in Cambridge, he had already produced about thirty instruments with primaries ranging in size from about $2\frac{1}{2}$" to 15".(10) The metal mirror telescopes were specifically described as being Gregorians, which has led Turner to conclude that the glass mirror instruments were Newtonians.(11) With the largest of these Gregorians, Short and Bayne had read at the most impressive distance of 500 feet, and

> "have several times seen the five Satellites of Saturn together, ... which very much surprised me till I found that Mr. Cassini had sometimes seen them all with a seventeen foot refracting telescope." (12)

Maclaurin had other Gregorians to hand, and Short found that by taking sufficient care of the figure of his mirrors "he finds himself able to give them larger apertures than other workmen do": he had made mechanical improvements too, and "takes vast pains to make the instruments as perfect as possible". The most telling comparison Maclaurin made was between a 6 inch instrument by Short and "one of the best I have seen from London" of 9.3 inches: Short's was found "to exceed it in brightness, distinctness and magnifying power".

What reaction this letter received is not known, but a positive response was certainly given to a letter Maclaurin sent to George Graham, which the eminent horologist read to the Royal Society in June 1735.(13) Short was described as "an Artist in Scotland" who had made an "extraordinary Improvement of the Reflecting Telescope", allowing the satellites of Saturn to be seen "sufficiently luminous, as well as distinct" in an instrument of only 18 inches. Graham "undertook to procure one of the Instruments from Mr Maclaurin, in order to see how well it answered to the account given of it", and this he evidently did because in March 1736 Graham was observing an eclipse together with the Swedish scientist Andrew Celsius using a reflector by Short.(14)

In the summer of 1736 Short was able to visit London, having been summoned by Queen Caroline to tutor her son the Duke of Cumberland in Mathematics.(15) During his brief stay he met Graham and others in the Royal Society and impressed them with the quality of further telescopes he had brought with him. In September Short and Graham observed another eclipse using the smallest of these, a $5\frac{1}{2}$" instrument.(16)

The tests comparing the performance of Short's reflectors with those of other makes may have been the idea of the astronomer John Bevis (1693-1771, F.R.S. 1765), and comparisons in June and July 1736 were constructed in his house in Islington with George Graham and others.(17) At the third trial in September Short was also present and he saw his instrument outclass the others. A report of the trials was submitted to the Society in December, and Short was forthwith proposed for election as having "lately distinguished himself by his Excellent Reflecting Telescopes".(18)

Short had returned to Scotland by November, and through Maclaurin was becoming known to the small group of men in and around Edinburgh who were interested in scientific matters. In early 1736 he was observing a solar eclipse in conjunction with Maclaurin, Sir John Clerk of Penicuik and the Earl of Morton, who was to become his patron. Later that year Alexander Monro's Society for the Improvement of Medical Knowledge was revived as the Society for Improving Philosophy and Natural Knowledge, later to become the Royal Society of Edinburgh. Morton, Clerk and Maclaurin were the principal office-bearers and

Short, newly elected to the Royal Society of London, was the only one amongst the founder members who earned a living by trade.[(19)]

His education and his mathematical ability, however, raised him above the level of an artisan and led to a more ready acceptance in scientific circles, giving him access in the process to a market for his instruments. By mid 1736 his efforts had rewarded him to the extent of £500 which he was able to deposit in the Bank of Scotland.[(20)]

Encouraged by his reception in London, and attracted by the prospect of working in what was then the thriving centre of instrument-making in Europe, Short moved to London in early 1738. He established a workshop in Surrey Street off the Strand, and soon gained a reputation for his technical and scientific ability. His high standing brought him membership of the Royal Society's Council, and is reflected in his contributions to the preparations for the transits of Venus in the 1760s, and in his association with the work of the Board of Longitude. Latterly he was considered the best qualified candidate for the position of Astronomer Royal on the death of Nathaniel Bliss, but he lacked influential support at the time and was not chosen.[(21)]

The popularity of Short's product was undoubtedly enhanced by the publication in the year he moved to London of Robert Smith's <u>Compleat System of Opticks</u>.[(22)] This comprehensive treatise became probably the most influential optical textbook of the 18th century, and it was as remarkable for its contributions to geometrical optics as it was significant for the strictly corpuscular dynamical interpretation placed on Newton's optical work.[(23)] Smith's work was recommended by contemporaries such as the enthusiastic Newtonian disciple J.T. Desaguliers, and was widely read both in Britain and on the Continent. The third book of his <u>Compleat System</u> was the 'Mechanical this he evidently did because in March 1736 Graham was observing an eclipse together with the Swedish scientist Andrew Celsius using a reflector by Short.(14)

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Already by late 1734 Short had been able to employ larger apertures than other makers by "taking care of the figure", and this feature of his instruments was readily apparent at the 1736 tests also.[(28)] Short's success in this respect was due to his ability to parabolise his mirrors: Smith, having explained that the spherical aberration of the Gregorian form was greater than that of the Newtonian, noted that it should be "diminished by correcting the spherical figure of the large speculum, and inclining it towards a parabolick, which Mr. Short takes constant care to do."[(29)] Although Short provided no account of his mirror making practice, the Plymouth physician John Mudge visited Short's workshop, and in 1777 after Short's death he presented a detailed investigation of the founding and figuring of metal mirrors at the Royal Society, and revealed some of the methods he believed Short to have used.

Mudge's careful experiments led him to adopt a binary alloy of 32 ounces of copper to $14\frac{1}{2}$ ounces of tin, which was close to Molyneux's alloy and was subsequently little improved on. Turner has suggested that Short's experience in seeking a hard metal whose surface did not break up on grinding will have been the same as Mudge's, and that the composition of Short's specula will have been closely similar.[(30)] The troublesome microscopic porosity was avoided by first casting the metal into an ingot and then re-melting this to cast the mirrors at a lower temperature. Although Mudge suspected this method was known, he had frequently seen porous metals; he had even "observed metals of some of Mr. Short's telescopes which are not quite so perfect as could be wished", and the implication is that whatever method Short used to reduce porosity, it was generally but not completely successful.[(31)]

The grinding process described by Mudge was similar to that in Smith's Opticks, but the polishing was done by a different method. Mudge deduced from the nature of the polish of the metals, and the lack of minute scratches, that Short had not used a cloth-based pitch polisher but had polished directly on pitch. Mudge's polishing tool was much simpler than Hadley's and used pitch spread on a convex tool, with putty ground into its surface. By experience Mudge developed a technique for perforated Gregorian mirrors, using a polishing tool that was itself perforated, "which I have strong reasons to believe was Mr. SHORT'S method".(32) Having produced a truly spherical surface, a parabolic figure was imparted to the mirror by a procedure that involved establishing the best contact between the polisher and the mirror, then polishing briefly with a spiral motion to increase the curvature slightly at the centre of the mirror.(33)

Mudge tested the final parabolic figure by mounting the mirror in its tube, complete with secondary and eyepiece, and viewing a watchglass placed at about 20 yards distant. Annular stops at the end of the tube obscured either the peripheral or central zone of the mirror, and if the focal position was found to be the same then the mirror was assumed to be parabolic.(34)

The optical performance could be further improved by rotating the primary mirror in its mount until the most distinct image was obtained, when the orientation of the two mirrors was such that their aberrations most nearly cancelled each other. Short then marked the upper part of the mirror with a line of black paint, and in the instructions supplied with his telescopes he cautioned:

> "There is a black Stroke on the Back of the Great Mettal, and Care must be taken, that this Stroke always points upwards from the Hole." (35)

Clearly, before this could be effective the astigmatism of the two mirrors had to be similar. By interchanging the mirrors of different telescopes by Short, Mudge observed that the primary and secondary mirrors seemed to be matched, and performed less well when used in different combinations. He proposed that Short took pains to pair his mirrors by selecting from a stock of finished primaries, and indeed when Mudge visited his workshop Short "shewed me himself a box of finished metals, in which I am sure there were a dozen and a half of the same focal length."(36) This suggestion is perhaps borne out by the fact that the serial numbers indicate that Short's smaller instruments were completed in batches.

In James Short's hands the reflector's potential was at last realised, and the instrument became a reproducable and dependable tool. Short was perhaps fortunate in working at a time when rapidly increasing popular interest in science created a new market ready to be stimulated by just such a new instrument, and at a time also when national and institutional science across Europe was active and there were important commissions to attract. Short's manufacturing example encouraged other makers to emulate him, and although this contributed to the buoyant and competitive instrument market of the mid 18th century, Short maintained an unquestioned lead over his contemporaries. By 1740, when Short was securely established in London, the reflecting telescope can be said to have 'come of age', and the pattern of its commercial development was largely set for the next 40 years.(37)

Notes and References

1. Turner (1967), (1969), (1971); Bryden (1968), (1969), (1970).
2. Turner (1973).
3. Erskine (1792), 252.
4. Maclaurin (1748), v.
5. Bryden (1970), 253.
6. Maclaurin (1748), iii.
7. Bryden (1970), 254.
8. Erskine (1792), 253.
9. This early work is described in Maclaurin's letter of 28 December 1734, printed in Smith (1738), Remarks pp.80-81.
10. It is normally assumed that the letter was addressed to Smith. Buchan however describes it as having been sent to James Jurin: Erskine (1792), 253. Jurin's 'Essay on Distinct and Indistinct Vision' was appended to Smith (1738).
11. Turner (1969), 97.
12. Smith (1738), Remarks p.81.
13. Roy. Soc. MS Journal Book, meeting of 26 June 1735.
14. Bryden (1970), 255.
15. Erskine (1792), 254. The Queen had earlier been impressed with a 'history of the progress which philosophy had made before Sir Isaac's time' which Maclaurin had written shortly after Newton's death: Maclaurin (1748), vi.
16. Bryden (1970), 255. John Bevis described this instrument by Short as "the first Reflector he ever made": see below, ref (17).
17. The tests were conducted on 15 June, 8 July and 25 September 1736 and Graham and Bevis were present at each. Amongst others who

attended were the instrument-makers Thomas Heath and Edward Scarlett, and two of Short's sponsors for his election to the Society, Martin Folkes and Richard Graham. The account by Bevis of these trials was read at the Royal Society on 16 December 1736 and is entered in the letter book: Roy. Soc. MS LBC.23.88-95. Some details of the instruments examined were published in Court & von Rohr (1929), 220, from a copy of Bevis' report in the British Library (MS Add.4433): here the 15 June test is described as having been made on 16 December, the 8 July test is omitted but the list of those present is given for 16 December also.

18. Turner (1969), 92.
19. Bryden (1970), 255.
20. Erskine (1792), 254.
21. Short had lost the support of the Earl of Morton, who was newly elected as President of the Royal Society, because he was pressing John Harrison's claim for the longitude prize: Bryden (1970), 258.
22. Smith (1738).
23. Steffens (1977), 34-50.
24. For example, the dimensions given for Gregorian and Cassegrain reflectors are based on information provided by Short: Smith (1738), Remarks pp.103-6.
25. Although Mortimer's Directory of 1763 described him as an 'Optician solely for Reflecting Telescopes', Turner has noted that two lots at the sale of his stock at his death were reflecting microscopes: Turner (1971), 105. Short also ground glass object glasses for Bradley's use at Greenwich in 1749: Rigaud (1832), lxxx.
26. Turner (1969), 100-2; Turner (1973), 26-7.

27. Bryden (1968), 31.

28. Smith (1738), Remarks p.80.

29. Ibid, Remarks p.104.

30. Turner (1969), 98.

31. Mudge (1777), 303.

32. Ibid, 327.

33. Ibid, 333.

34. Ibid, 335.

35. Turner (1969), Plate 10.

36. Mudge (1777), 340.

37. A number of proposals made about this time are of interest on theoretical grounds but made no impact on telescope construction practice. An example is Caleb Smith's compound 'achromatic' reflector of 1740 (see e.g. Court & von Rohr (1929), 223), and another is Servington Savery's little known front-view telescope of 1733 (Roy. Soc. MS LBC.21.92.95).

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